PB 188 092

AIR POLLUTION ASPECTS OF RADIOACTIVE SUBSTANCES

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September 1969

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AIR POLLUTION ASPECTS
OF
RADIOACTIVE SUBSTANCES

Prepared for the
National Air Pollution Control Administration
Consumer Protection & Environmental Health Service
Department of Health, Education, and Welfare
(Contract No. PH-22-68-25)

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September 1969

FOREWORD

As the concern for air quality grows, so does the concern over the less ubiquitous but potentially harmful contaminants that are in our atmosphere. Thirty such pollutants have been identified, and available information has been summarized in a series of reports describing their sources, distribution, effects, and control technology for their abatement.

A total of 27 reports have been prepared covering the 30 pollutants. These reports were developed under contract for the National Air Pollution Control Administration (NAPCA) by Litton Systems, Inc. The complete listing is as follows:

- Aeroallergens (pollens)
- Aldehydes (includes acrolein and formaldehyde)
- Ammonia
- Arsenic and Its Compounds
- Asbestos
- Barium and Its Compounds
- Beryllium and Its Compounds
- Biological Aerosols (microorganisms)
- Boron and Its Compounds
- Cadmium and Its Compounds
- Chlorine Gas
- Chromium and Its Compounds (includes chromic acid)
- Ethylene
- Hydrochloric Acid
- Hydrogen Sulfide
- Iron and Its Compounds
- Manganese and Its Compounds
- Mercury and Its Compounds
- Nickel and Its Compounds
- Odorous Compounds
- Organic Carcinogens
- Pesticides
- Phosphorus and Its Compounds
- Radioactive Substances
- Selenium and Its Compounds
- Vanadium and Its Compounds
- Zinc and Its Compounds

These reports represent current state-of-the-art literature reviews supplemented by discussions with selected knowledgeable individuals both within and outside the Federal Government. They do not however presume to be a synthesis of available information but rather a summary without an attempt to interpret or reconcile conflicting data. The reports are necessarily limited in their discussion of health effects for some pollutants to descriptions of occupational health exposures and animal laboratory studies since only a few epidemiologic studies were available.

Initially these reports were generally intended as internal documents within NAPCA to provide a basis for sound decision-making on program guidance for future research activities and to allow ranking of future activities relating to the development of criteria and control technology documents. However, it is apparent that these reports may also be of significant value to many others in air pollution control, such as State or local air pollution control officials, as a library of information on which to base informed decisions on pollutants to be controlled in their geographic areas. Additionally, these reports may stimulate scientific investigators to pursue research in needed areas. They also provide for the interested citizen readily available information about a given pollutant. Therefore, they are being given wide distribution with the assumption that they will be used with full knowledge of their value and limitations.

This series of reports was compiled and prepared by the Litton personnel listed below:

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Appreciation is expressed to the many individuals both outside and within NAPCA who provided information and reviewed draft copies of these reports. Appreciation is also expressed to the NAPCA Office of Technical Information and Publications for their support in providing a significant portion of the technical literature.

ABSTRACT

Radiation produces somatic effects (for example, leukemia) and genetic effects in man. Since the genetic effects of various amounts of radiation cannot always be determined, many scientists accept the belief that there appears to be no threshold for the biological damage from radiation.

Atmospheric radiation arises both from natural sources—such as rocks, soils, and cosmic rays—and from artificial sources, such as nuclear explosions and the nuclear industry in general. Experience to date has shown that the amount of radiation reaching the general public through releases from the nuclear industry is insignificant when compared with the natural radiation dose, even though there is a potential for radiation release from all facets of the nuclear industry. However, because of projected nuclear expansion, there is evidence that krypton-85 released from fuel reprocessing may be a problem. The dose to the population from nuclear weapons testing was more significant, amounting to levels about 5 to 10 percent higher than the levels of natural radioactivity. The United States Atomic Energy Commission has established maximum permissible concentrations for radionuclides that can be released from nuclear plants.

Extensive efforts are employed in the nuclear industries to prevent emission of radioactive substances into the atmosphere. The cost of these abatement procedures has been

estimated at approximately 10 percent of the total cost of the nuclear plant. No information has been found on the costs of damage resulting from radioactive pollution of the atmosphere.

Many methods with a high degree of accuracy and sensitivity are available for the determination of atmospheric concentrations of radioactive substances.

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1. INTRODUCTION

Atmospheric pollution by radioactive substances originates as natural radioactivity that emanates from rocks or as artificial activity, which is a by-product of the nuclear industry.[55] Natural radioactivity was first discovered by Becquerel and the Curies at the turn of the century, while artificial sources (nuclear fission) were discovered by Hahn and Strassman about 30 years ago. The air pollution aspects of radioactivity did not become apparent, however, until after the development of the atomic bomb and the techniques for harnessing nuclear energy during World War II.

Prior to World War II, environmental radioactivity was a natural phenomenon which was studied by the relatively few highly specialized laboratories equipped to make radioactivity measurements. During World War II, the construction of large nuclear reactors and plutonium extraction facilities at Hanford and uranium enrichment facilities at Oak Ridge created the first opportunity for artificial radioactive pollution of the atmosphere. However, studies of the behavior of various radionuclides that were released to the environment have shown that although caution must be used in the process, large amounts of radioactive materials can be safely discharged if the diffusion and dispersion properties of the atmosphere are well known.[22,55]

Evidence of the harmful effects of indiscriminate exposure to radiation began to accumulate shortly after the discovery of X-rays in 1895, and recommendations for limitations of exposure were soon made. This knowledge of the harmful effects of radiation led the Manhattan Engineering District (the wartime military organization responsible for the atomic energy program) to place a high priority on keeping environmental contamination to a minimum. When the Atomic Energy Commission (AEC) succeeded the Manhattan Engineering District in 1946, these cautious policies were continued. Around the same time (1947), the Public Health Service established a Radiation Energy Unit, later called the Radiological Health Unit, within the Division of Industrial Hygiene to handle the public health aspects of radiological health problems.[49] In the United States, the Soviet Union, and the United Kingdom, a series of weapons tests were conducted during the 1940's and 1950's that discharged larger amounts of radioactivity into the environment than were permitted by the AEC in the operation of its industrial plants. This radioactivity soon become widespread throughout the atmosphere, contaminating soil and food to such an extent that worldwide apprehension began to develop. The Congress of the United States then held a number of hearings[82,128] on fallout from weapons testing and on radioactive waste-disposal practices. Around the same time, the National Academy of Sciences[132] in the United States and the Medical Research Council in Great Britain began to evaluate the effects of small doses of radioactivity. In 1955, the United Nations appointed a committee to investigate the effects of radiation on man.

Since World War II, extensive research has been conducted on the physical and chemical properties of radioactive substances. The manner in which they are transported physically through the environment and the way in which some of them enter into man's food supplies, the water he drinks, and the air he breathes, have been studied. Many branches of the biological and physical sciences have been involved in this study.

Man can be contaminated by radiation both directly and indirectly. The direct methods include exposure to radiation emitted by radioactive gases or suspended dust, resulting in either contamination of the skin or of the respiratory tract. After a radioactive contaminant is inhaled, the radioactive substances can be concentrated inside the body, depending on the selective power of fixation of organs for which the radionuclides show a special affinity. Except in a few cases, the concentrations reached are relatively small. The direct type of contamination occurs primarily where there is an occupational hazard or in the immediate neighborhood of nuclear reactors.

Indirect contamination results from ingestion of radionuclides after they have passed through the food chain. The contaminating radionuclide may follow an extremely complicated path while passing down the food chain. Radioactive contaminants suspended in air can be deposited on the ground or on surface water. The contamination from the soil and water is then passed on to vegetation and eventually to animals. The fate of the contaminant will depend on the biological cycle for each organism, as well as on nutritive exchanges between vegetation and animals.[199] During these exchanges, secondary—and often high—concentrations will be produced in some organisms.[89] Plants tend to concentrate radioactivity more in the leaves and stems than in the seeds. For man, the varied diet which he enjoys multiplies the sources of contamination. For example, milk is a source of indirect contamination. Therefore, indirect contamination can affect whole populations.

Since radiation cannot be detected without special instrumentation and its biological effects are usually not evident until some time after the exposure, a series of regulations have been developed to protect both the general public and the occupational worker.

In 1928, the International Commission on Radiological Protection (ICRP) was organized under the auspices of the Second International Congress on Radiology. In 1929 the Advisory Committee on X-ray and Radium Protection was organized to develop recommendations in the United States. Following World War II, this advisory committee was reorganized as the National Committee on Radiation Protection (NCRP). The recommendations developed by this group have served as the basis for most radiation-protection programs and, later, for rules and codes adopted by the various regulatory agencies in the United States. In 1959 the Federal Radiation Council (FRC) was formed to advise the President on radiation matters and to guide all federal agencies in formulating standards for protection against radiation damage. In 1949, Public Health Service activities in radiological health were accelerated when the Radiological Health Unit became the Radiological Health Branch in the Bureau of State Services. In 1958 the Surgeon General established the Division of Radiological Health with six major responsibilities. These were (1) research on the effects of radiation on living matter, including man; (2) development of methods, facilities, and programs for collecting, collating, analyzing, and interpreting data on all forms of radiation exposure throughout the United States; (3) training of the scientific, professional, and technical workers needed in the rapidly expanding radiological health programs of Federal, State, and local agencies; (4) technical assistance to Federal, State, and local agencies as needed; (5) development of recommendations for acceptable levels of radiation exposure from air, water, milk, medical procedures, and the general environment; and (6) public information and health education activities related to radiological health. The division was succeeded by the National Center for Radiological Health which in 1968 became the Bureau of Radiological Health in the Environmental Control Administration of the Consumer Protection and Environmental Health Service, Department of Health, Education and Welfare.[49]

The ICRP and the NCRP were first concerned with recommendations for X-ray and radium protection. In 1936, NCRP first recommended specific permissible exposure levels (tolerance doses) for radium. NCRP has since published a series of handbooks covering various aspects of radiation protection, instrumentation, and environmental contamination.[112,133]

The ICRP and NCRP have recommended similar maximum permissible concentrations (MPC) for a wide variety of radionuclides in air and water.[112,128,144] These are recommendations only and have no legal status. In November 1960 the AEC published in the Federal Register[33] a regulation which became effective January 1, 1961, establishing general standards for protection of licensees, their employees, and the general public against radiation hazards arising out of the possession or use of special nuclear source or by-product material under license issued by the AEC.

Throughout the text of this report, a number of terms unique to the nuclear energy field are used to quantitatively describe radiation and its biological effects. The definitions of these terms can be found in Appendix A.

2. EFFECTS

2.1 Effects on Humans

Evidence on the harmful effects of indiscriminate exposure to X-rays began to accumulate shortly after the discovery of X-rays in 1895 when the ability of X-rays to cause loss of hair, burns, chronic ulcers, and cancers was observed. During and following World War I, workers using radium in the luminous paint industry developed bone cancer and aplastic anemia due to radium ingestion.[61,110] During the 1920's, additional deaths were caused by the use of radium as a nostrum for a variety of ailments such as arthritis, syphilis, and others. Miners in Joachimsthal, Czechoslovakia, had high rates of lung cancer, which by 1949 was thought to be caused by high concentrations of radon and its daughter products in the mine atmosphere.[107,187] Evidence confirming this among workers in the U.S. uranium mining and milling industry was supplied by Wagoner et al. in 1964.[187,188]

Early in this century, it was discovered that sufficient ionizing radiation doses could cause sterility and changes in composition of peripheral blood. If acute exposure occurred, a complex set of symptoms (nausea, vomiting, hemorrhage, diarrhea, loss of weight, and severe anemia) was observed that is now known as the acute radiation syndrome.[55] On the positive side, it was discovered that cancerous tissue could be injured by ionizing radiation, and this fact forms the basis for radiation treatment of cancer.

The Division of Radiological Health of the Public Health Service (currently the Bureau of Radiological Health, Environmental Control Administration, Consumer Protection and Environmental Health Service, Department of Health, Education, and Welfare) prepared a Select List of References on Human Studies. Table 1, Appendix B, shows the number of papers on each subject that were in the Select List in 1964.

2.1.1 Types of Exposure

Two major types of radiation exposure may result from radioactive pollution of the atmosphere: exposure to radiation from a distant source, and contamination by radioactive substances which come into contact with the skin or find their way into the body.

External radiation exposure can occur only from radionuclides emitting gamma rays from sources such as solid decay products of radon in suspension in the air and radioactive gases, such as argon-41. The most serious hazard is external or internal radioactive contamination. External contamination occurs when radioactive particles suspended in the atmosphere are deposited on the surface of the skin. This may result in cutaneous irradiation, whole-body irradiation, or internal contamination via the respiratory or digestive tract.

Respiratory tract contamination is the most direct and important effect of radiation pollution. The digestive route, which is indirect, is the route followed after contamination of foodstuffs, or sometimes after cutaneous or respiratory contamination. Persons engaged in radiation work (occupational exposure) are subject to a different type of exposure than the population at large. These workers are particularly prone to skin and respiratory contamination, whereas the main hazards for the general population are direct exposure to radioactive substances in the atmosphere and indirect contamination through ingestion.

The average ionizing radiation dose rate received by persons living in the United States from various sources is shown in Table 2, Appendix B.

2.1.2 Biological Effects

Ionizing radiation produces a variety of biological effects, depending upon the dose of radiation received and whether it is delivered in a short or long period of time. Some effects, such as changes in skin texture or hair pigmentation, occur soon after exposure, while other effects, such as leukemia and cataracts, may not appear for five or more years. The effects that occur in the exposed individual are called somatic effects. The genetic effects of radiation are observed in the descendants of the exposed person.

2.1.2.1 Somatic Effects

The most important somatic effects from ionizing radiation are leukemia and other types of cancer, cataracts, and reduction in life expectancy. Data on somatic effects of radiation have been derived from animal experiments; from observations made on patients treated by radiotherapy or radioisotopes; from studies of radiologists, and other workers exposed to ionizing radiations or poisoned by radioactive substances; and from Japanese survivors of Hiroshima and Nagasaki.

2.1.2.1.1 Leukemia

There has been an increased incidence of leukemia among the Japanese survivors of Hiroshima and Nagasaki,[15,16,21,84,190] radiologists,[44,53,84] patients irradiated for ankylosing spondylitis,[42] and children irradiated for thymic enlargement. The radiologists received their doses in repeated small quantities. The others were subject to acute exposure. There is also evidence that leukemia can be induced in children irradiated for therapeutic or other diagnostic purposes.[95]

Information to date on radiation-induced leukemia is limited to the effects of a dose range between 100 and 1,000 rems; no cases of leukemia induced by exposures of less than 125 rem have been identified.[81] However, leukemia has been induced in the fetus by doses which ranged between 2 and 10 rem.[27] In recent years, the incidence of leukemia in radiologists has decreased.[192] This is attributed to the fact that most radiologists now keep their received doses below current recommended maximum permissible dose levels. These maximum permissible levels allow for a total lifetime dose of 250 rems.

Therefore, there seems to be a lower threshold for radiation-induced leukemia that is somewhere below 100 rems. Many experimenters accept the threshold theory, although there is some disagreement among them.[99,100,106] The number of cases induced by lower dose levels are too few to form any firm conclusions.

2.1.2.1.2 Other Cancers

Radiation has produced skin cancers among radiologists, thyroid cancer in children irradiated in the neck region, lung cancer in miners and millers occupationally exposed to radon and its daughters, and bone cancers in radium dial painters and other persons exposed to radium.

Bone cancer (osteogenic sarcoma) can be produced by irradiation when radioelements similar to calcium, such as radium, radioactive strontium, radioactive plutonium, radioactive thorium, and radioactive lead are ingested and metabolized into the bone. Bone cancer was observed among luminous paint workers and radium-treated patients early in this century.[55,148] External radiation can also produce bone cancer, and a few cases have been reported.[95] However, a high dose (3,000 to 4,000 rads) is thought to be required.[95]

Lung cancer can result from inhalation of radioactive gases or dust, such as radon and its daughter products.[51] As early as 1879, there was evidence of increased prevalence of lung cancer among the metal miners in Schneeberg in Saxony. By 1949 most investigators were attributing this and the increased cancer in miners in Joachimstahl, Czechoslovakia, to radon and its daughter products in the mine atmosphere.[107,187] In 1964, Wagoner and his coworkers[187,188] reported an excessive occurrence of respiratory cancer among uranium mine workers in the United States and demonstrated a dose-response relationship. However, the complete quantitative statement of the dose-response relationship cannot be established at the present time because the number of individual studies and the periods of observation at low exposure levels are still inadequate,[40] particularly at the lower levels of exposure to radon and its daughters.

Evidence of radiation-induced lung cancer was also noted in fluorspar mines in Newfoundland, where abnormal levels of radon and its daughter products were present in the mine atmosphere.[40]

The ability of the lung to concentrate particulates increases the relative risk of inhaling radioactive aerosols as compared to the risk of inhaling a radioactive gas. The radon daughter products attach themselves to the atmospheric dusts, thus making these dusts the principal hazard in the uranium mines.[187] According to Shapiro[157] in 1956, the daughter products contribute about 20 times as much dosage as does the radon.

The dose received by the different portions of the lungs from inhaled radioactive dust depends on the concentration of radionuclide in the inhaled air, the physical properties of the radionuclide, the rate at which the dust is inhaled, the region of the lung in which the dust is deposited, and the rate at which it is removed. Theoretical lung models have been developed for computing the dust deposition in and clearance from the respiratory tract to provide a basis for calculating lung dosimetry and for setting exposure limits.[126] However, the dose required to produce lung cancer in man is not known.

A number of studies have been made on the frequency of occurrence of thyroid cancer in children and adults irradiated in the thymus region for benign conditions. Most studies showed an increase in thyroid cancer, although some did not.[27] Hiroshima and Nagasaki data indicate that the adult thyroid may be less sensitive to radiation than a child's thyroid.[95] Since the thyroid tends to concentrate iodine and will therefore concentrate radioactive iodine, the potential for forming thyroid cancer from irradiation is an important reason for minimizing radioactive iodine releases to the atmosphere.

2.1.2.1.3 Cataracts

Exposure of the lens of the eye to heavy doses of X-rays, gamma rays, beta particles, and neutrons may cause eye cataracts (opaque spots). Although lens changes have been reported from doses as low as 200 rad, the minimum X-ray or gamma ray dose capable of causing clinically significant cataracts is thought to lie between 550 and 950 rads (averaging about 800 rads) in adults and perhaps less in children.[95,106,119] If an average dose of about 800 rads is delivered over a period of 2 weeks to 3 months, it may produce an opacity in 70 percent of those exposed. About 30 percent of these opacities may be progressive and eventually result in impaired vision.[95] The development of cataracts is much more likely to result from neutrons than from X-rays or gamma rays.

Cataracts have been observed among the Japanese survivors of Hiroshima and Nagasaki; among patients whose eyes were treated by X-rays, gamma rays, or beta rays for medical purposes; and among a few physicists who were exposed to the radiation from cyclotrons.[95]

2.1.2.1.4 Effect on Life Span

Whole-body irradiation of experimental animals has been found to result in shortened life span.[122,133] In addition, there are indications of life-span shortening in radiologists. The life-span shortening could not be attributed to a radiation-induced fatal disease such as leukemia, but rather to an apparent acceleration of the aging process.[155,191] Since 1935, the evidence of life shortening in radiologists has decreased, and by 1960 it had disappeared. This can be attributed to the more rigid radiation protection techniques adhered to by radiologists in recent times.[192] Data from experiments with rodents and other animals indicate that the reduction in life span becomes greater as the dose increases.[106,147] No definitive data exist on the dose-response relationship for general life shortening in man.[95] Theoretical models have been developed extrapolating radiation exposure and life span shortening in experimental animals for use in assessing human effects. Sacher,[151] extrapolating data from small animals to man, developed a theoretical life-span reduction of 17 days per rad. However, this quantitative relationship was not seen in the Hiroshima data. The value is thought to be too high, and work to establish a better value is in progress at Argonne National Laboratory.[151]

2.1.2.2 Genetic Effects

Radiation can produce mutations in human gametes which will not be apparent in the person irradiated but which may appear in future generations.[52]

Genetic injury to a population depends on the total number of mutant genes introduced. The measure of potential damage is the total number of man roentgens delivered to the gonads—the "per capita" gonadal dose. A small dose delivered to the whole population may thus produce more genetic damage than a much larger dose delivered to a relatively small fraction of the population.

It is estimated that about 1 percent of live-born infants suffer from severe effects of chromosomal abnormalities which arise spontaneously. The extent to which natural radiation contributes to this is not known.[147]

An estimate of the average dose over the reproductive lifetime of the individual which is required to double the mutation rate is between 10 and 100 rads.[183] That is, if an average dose of between 10 and 100 rads were delivered to each generation, a new equilibrium would in time be reached in which mutant characteristics would be seen twice as frequently as in the original population.

2.1.2.3 Acute Exposure

Acute exposure is primarily a hazard to people in the nuclear industry (occupational exposure). The general public will not be exposed in this manner except in wartime or following a nuclear accident in which large quantities of radioactive materials are released to the atmosphere. When a massive whole-body dose of radiation is received within a short period of time, the effects may be seen as early as the first day and will be dependent on the size of the dose received. Only minor injury would occur at doses less than 100 rems, but about a 50 percent fatality rate would be expected in the range of 400 to 500 rems. As the whole-body dose approaches 1,000 rems, fatalities would approach 100 percent. Table 3 in Appendix B summarizes the expected clinical effects of acute doses of ionizing radiation. At doses of less than 100 rems, no significant symptoms are likely to be seen, but as the dose increases above 100 rems, vomiting and nausea occur in increasing frequency and will be seen in almost all exposures of about 300 rems. At 100 to 250 rems, the nausea and vomiting may be followed by a latent period of as much as 2 weeks. However, this latent period is less than a day at doses greater than 700 rems. The signs and symptoms which then develop—known as radiation syndrome—usually include epilation, sore throat, hemorrhage, purpura, petechiae, and diarrhea.

Acute radiation causes illness primarily by damaging the blood-forming centers in the bone marrow and lymph glands.[74,189] Acute radiation exposure from inhalation or ingestion of radionuclides is not a problem, since the principal exposure in environments contaminated with fresh fission products is from external radiation.[55]

2.2 Effects on Animals

2.2.1 Commercial and Domestic Animals

The effects of radiation on animals are similar to those on humans. At high radiation doses, acute radiation effects develop within a period of a few hours to a few weeks.[26] In cattle, 50 percent fatality would be expected after a dose of 520 to 570 r.[47] There is also some evidence that whole-body irradiations of 100 to 400 r can temporarily produce a reduction in conception.[47] The $LD_{50/30}$ dose rates for other commercial animals are shown in Table 4, Appendix B.

Acute exposure of domestic animals would only occur through direct radiation from a nuclear explosion or nuclear accident which released large quantities of radioactive substances to the environment.

At lower radiation levels, the effects are either delayed or long-term. These effects include leukemia, cancer, shortening of life span, and genetic or mutation effects.[26]

Even at times of high nuclear test fallout, grazing animals receive most of their radiation from ingesting airborne nuclides deposited on forage. Grazing animals have a high tolerance for ingested radionuclides, which are poorly absorbed. Of the absorbed radionuclides, iodine is the most hazardous because it concentrates in the thyroid. However, this hazard can be counteracted in most animals by feeding them thyroactive compounds.[13] The primary observed effect from radioactive fallout has been external damage to skin and hair.

For example, during the detonation of the first atomic bomb in 1945, a herd of Hereford cattle that were located about 15 miles from the detonation site were accidentally exposed to high levels of radiation from radioactive fallout particles. Thirty-two of these cattle were purchased by the government for observation. Except for surface damage to skin on the sides and backs of the animals produced by direct contact with radioactive particles, the general condition, productive efficiency, and death rate were comparable to that of control cattle.[13] One cow from the herd lived 20 years with little apparent effect except for some hair that turned grey; it produced 16 healthy, frisky calves.[148] At Las Vegas, Nev., various free-range animals (mountain goats, deer, and livestock) that are exposed to low-level radiation from the Nevada Test Site are periodically examined for radiation content and radiation health effects. The animals have been studied within the nuclear test site and up to 200 miles from the test site for about 10 years. Although strontium-90 has been found in the bones and cesium-137 in the flesh of the animals, examination of the tissue has shown no apparent radiation damage to date.[113,172]

Commercial animals are an important link in the food chain by means of which radioactive contamination released to the atmosphere finds its way to man. Animals consume plants which contain radionuclides deposited on them or absorbed from the soil, and tend to concentrate the radionuclides strontium-90, iodine-131, sesium-137, and others in their flesh or milk. For man, the maximum tolerable level for contamination from this route is not known.[26]

2.2.2 Experimental Animals

Millions of experimental animals of all types are being used in nearly every laboratory where nuclear research is conducted. A recent Atomic Energy Commission inventory showed that more than 6 million animals per year are used in AEC-sponsored research. A list of the types and number of experimental animals used in the programs of the Division of Biology and Medicine of the AEC is shown in Table 5, Appendix B.

Work on the effects of radiation on animals in 1897 showed that radiation produced cataracts in animals.[31] In 1927 Muller[9] produced mutations in fruit flies by means of X-rays. A great amount of research since 1942 has been directed at understanding the mechanisms of these injuries.

Evidence from animal experiments has indicated that mutations can have dominant deleterious effects.[32,150]

As mentioned above, early estimates of genetic hazards were based on experiments with Drosophila (fruit flies). However, later experiments with mice showed greater radiation-induced mutation frequencies, indicating that the genetic hazard to man was greater than had been initially assumed.[150]

The results of irradiation experiments on mice and the indicated genetic hazard to man are as follows:[95,147,150]

(1) The more mature male germ cells (spermatozoa) are more sensitive to genetic damage than the stem cells (spermatogonia). The spermatozoa do not survive very long in

the body. The process from spermatogonial cell to mature spermatozoan takes about 5 weeks in the mouse and around 10 weeks in man. Therefore, some reduction in risk of transmitting genetic damage can be achieved by postponing procreation for a few weeks after irradiation of the male to allow him to pass beyond the stage at which irradiated spermatozoa are present. Nothing is gained by further delay.

(2) For females irradiated with fission neutrons, the interval between irradiation and conception has a major effect on mutation frequency. The genetic hazard will be less when a long interval occurs between irradiation and conception.[27] There is some indication that a similar effect occurs with gamma radiation.

(3) There is a dose-rate effect on mutations. Mutation frequency is less per unit dose of radiation when the exposure is spread out over a long period of time. Low dose-rate exposures do not produce as many mutations as high dose-rate exposures.

(4) The dose-rate effect in females is considerably higher than in males.

(5) There is no evidence of a threshold dose rate, i.e., a dose rate below which no mutations occur. A non-threshold effect for mutation is generally accepted at the present time.[27]

Mice have also been used in experiments studying the effect of radiation on aging. Radiation accelerates the aging process, as was shown by an experiment using a group of 14-month-old mice. Only three of the irradiated mice survived—and these were gray and senile—while all the untreated group remained normal, healthy, and active.[45] Irradiation experiments on mice at Argonne National Laboratory have been used to theoretically extrapolate life-span shortening of man due to radiation.[151] A study by Sacher[151] on mortality statistics for mice, rats, guinea pigs, dogs, and horses extrapolated to man led to a theoretical life-span shortening in man of 17 days per rad. This is discussed further in Section 2.1.2.1.4.

Experiments with guinea pigs demonstrated that the body could repair itself even after receiving a sizable dose of radiation.[148] Dog experiments have shown that the effects of radiation depend largely on the part of the body exposed; for example, the leg can tolerate a higher dose than the stomach.

In experiments conducted at the University of Utah, beagles were injected with radium-224, radium-226, radium-228, plutonium-239, americium-241, thorium-228, lead-210, and strontium-90 to determine the internal effects of these radionuclides. It was found that these radionuclides are deposited in the skeleton, although plutonium and americium are also deposited in other tissue. The dogs in these experiments developed bone cancers, liver tumors, and other cancers.[111] From the experiments it was found that the alpha emitters were more toxic than originally believed, while the beta emitters (strontium-90) were less toxic.[111] Plutonium-239 contributes to a large incidence of fractures in leg bones, and radium-228 weakens bones throughout the body.[148]

Inhalation experiments have been run with beagles at Battelle Northwest Laboratories. In 1958 and 1959 the dogs were exposed to 1.0 to 3.0 μ ci per dog of plutonium oxide. Out of the 25 dogs exposed, 17 developed primary pulmonary tumors 9 to 10 years after exposure.[25]

Miniature swine were also used at Batelle Northwest Laboratories to study the effects of ingested strontium-90 at various dose levels. This substance was fed daily to the experimental animals. After 3 to 4 years of ingesting low levels of strontium-90, leukemia has developed.[25] The high levels of strontium-90 have produced bone tumors.

Experiments with monkeys indicate that high levels of radiation interfere with the functioning of an animal's nervous system In addition, experiments with sleeping rats and cats indicate that low levels of radiation may also affect functioning of the nervous system.[148]

2.3 Effects on Plants

The observable effects of radiation on plants range from mutations at low dose rate to growth inhibition and death at high dose rates. In general, radiation damage in plants is difficult to detect except at dose rates many times higher than those attained during worldwide fallout[117] or those normally encountered in ambient air.

Mericle and Mericle[118] found a higher mutation rate in tradescantia at a dose rate of 0.006 r per day than at 0.001 r per day. Miller[120] found that needle growth on pine seedlings was slightly inhibited at 20 r per day. More noticeable effects are likely at 100 r per day.

Plants become contaminated with radionuclides either through deposition from airborne radionuclides or absorption from the soil and may transfer these through the food chain to man.

2.4 Effects on Materials

There is no evidence at the present time to indicate that there is any detrimental effect on materials from the radiation levels encountered in ambient air or worldwide fallout.

2.5 Environmental Air Standards

Early clinical data seemed to indicate that there was a radiation damage threshold—that is, a point below which no damage occurs. Prior to 1950, the radiation protection standards were based on this threshold concept. However, recent evidence on genetic effects of radiation indicates that even small doses of radiation can produce mutations. Conclusive evidence is not available to disprove the possibility of somatic effects from small, chronic radiation doses to large populations. There is now a consensus that there is no level of radiation exposure below which there is absolute certainty that harmful effects will not occur to at least a few individuals when sufficiently large numbers of people are exposed. This means that any radiation protection standard must take into account some risk to an exposed individual or population. Therefore, recently established radiation standards have been based on the permissible dose concept. The permissible dose is defined as the amount of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable damage to a person during his lifetime.[181,195]

2.5.1 Maximum Permissible Dose (MPD)

The maximum permissible doses (MPD) for radiation workers recommended by the International Commission on Radiological Protection (ICRP)[142,143] and by the National Committee on Radiation Protection (NCRP)[133] are in basic agreement, although there are some minor differences. Some of the recommended maximum permissible doses for radiation workers are listed in Table 6, Appendix B.

Before the development of large nuclear facilities, exposure of the public to man-made radiation did not exist, except for medical purposes. Differing sets of recommendations for radiation protection have since been formulated for radiation workers and for the general public. In 1952 the AEC recommended that the exposure for the general public be limited to one-tenth the amount of occupational exposure. The ICRP[144] and the NCRP[133] adopted this recommendation a few years later.[195]

The Federal Radiation Council (FRC) in 1960 translated the recommendation into general guidelines for all Federal agencies. The FRC-recommended practice[62,63] limits the maximum dose for an individual from nonmedical sources to 0.5 rem/yr (whole-body) and states that the average dose to the population over a 30-year period should not exceed 5 rem to the gonads for males. The amount of exposure from natural background radiation is not taken into account in the recommendations.

2.5.2 Maximum Permissible Concentrations (MPC)

The maximum permissible concentrations (MPC) of radioisotopes in air and water are calculated on the basis of the maximum permissible dose to an organ. Both the radioisotope uptake and concentration in various organs are considered over a 50-year period.[112] To provide a standard basis of calculation, the ICRP has defined a "standard man" in terms of his intake of air and water, retention of particulates, and weight of organs.[143] Some of these parameters are listed in Table 7 in Appendix B.

The standard man is a hypothetical individual, and specific people vary significantly from this standard. However, the use of standard-man values provides an overall estimate of the doses that might be received by the average industrial worker.

The quantity of radionuclides in the body when the critical organ is being exposed at MPD is known as the maximum permissible body burden. (The critical organ is the organ that receives the highest radiation from the absorbed isotope.) The concentrations of the radionuclides in the air and water to which the body is being exposed at MPD are also the maximum permissible concentrations (MPC) in air and water, respectively. These are the maximum permissible concentrations for internal emitters. Where the possibility for external exposure exists, the permissible dose of radionuclides in air and water must be reduced. However, for the general public, opportunities for significant exposure arise mainly from internal radiation due to contaminated air and water, except in times of war when there is an increased probability of external exposure.

Periodically, the NCRP and ICRP publish maximum permissible values which are in general agreement for more than 130 radionuclides. The NCRP values have been given official status by the AEC[34] by making them generally applicable to installations licensed by the AEC.

The AEC regulations establish the average maximum concentration (MPC) of radionuclides that can be released to an uncontrolled or unrestricted area (for example, to the atmosphere from the top of the stack) over a period of time. The radionuclide MPC's in air that can be released to the atmosphere are shown in Table 8, Appendix B.

3. SOURCES

3.1 Natural Occurrence

The two major sources of natural radioactivity are the gases which emanate from minerals in the earth's crust and the interaction of cosmic radiation with gases in the atmosphere.

3.1.1 Radioactive Dusts

Soils and rocks contain naturally radioactive minerals such as radium-226 and radium-229 in variable amounts. The radioactive progeny of two nuclides, the noble gases radon-222 and radon-220 (thoron), emanate from the earth's crust and contribute greatly to atmospheric radioactivity.[55] Their concentration is higher in areas where there are substantial amounts of uranium and thorium ores. Therefore, these gases may occur as air pollutants in the vicinity of uranium mines, mills, and refineries, or where radium and its ores and by-products are processed.[92.168] Radon, with a half-life of 3.8 days, has a much higher probability of emanating from the earth's crust before it decays than thoron, which has a half-life of 54 seconds. The atmospheric concentration of these noble gases and their daughter products also depends on many geological and meteorological factors. The daughter products of thoron and radon attach themselves to the inert dust in the atmosphere, endowing these dusts with apparent radioactivity.[28,196] In addition, some dust particles from naturally radioactive minerals and soils also find their way into the atmosphere, but they contribute very little to natural radiation.[168]

3.1.2 Cosmic Rays

Interactions of cosmic rays with atmospheric gases produce a number of radioactive species, the most important of which are tritium, carbon-14, and beryllium-7. Of lesser importance are beryllium-10, sodium-22, phosphorus-32, phosphorus-33, sulfur-35, and chlorine-39.[168] These interactions produce electrons, gamma rays, nucleons, and muons. At low radiation levels the muons account for 70 percent of the cosmic radiation.[147]

3.1.3 Combustion Emissions

Fossil fuels contain radioactive materials that escape into the atmosphere when the fuel is burned. The radioactive nuclides that escape from fossil fuels during combustion are listed in Table 9 in Appendix B. Coal ash contains a number of radionuclides which originate from traces of uranium-238 and thorium-232. It has been estimated that uranium-238 and thorium-232 are present in coal in concentrations of 1.1 and 2.0 ppm, respectively. Fly ash released from the stack when coal is burned contains 10.8 μCi of radium-235 and 17.2 μCi of radium-226 per electrical megawatt (MW) per year.[176]

Oil-burning plants normally discharge nearly all of their combustion products into the atmosphere; a 1,000 MW station which consumes 460 million gallons of oil per year will discharge about 0.5 μCi of radium-226 and radium-228.[56]

A recent joint study[24] of natural gas from northwestern New Mexico and southwestern Colorado by the U.S. Public Health Service and the El Paso Natural Gas Company shows that radon-222 (a daughter of radium-226) is present in natural gas at concentrations ranging from 0.2 pCi/liter to 158.8 pCi/liter. There is a lack of data concerning concentrations of radon-222 in the stack effluent of natural gas power plants, but it can be assumed to be minimal because of the short (3.8 day) half-life of radon-222 and the relatively long time required for transit of the gas from the well to the plant where it is burned, as well as for storage. There will be some activity from the longer-lived daughter products of radon, but these are hard to determine since the daughter products occur as particulates and are subject to many removal forces.

3.1.4 Natural Radioactivity

Measurements have been made of ground-level atmospheric radioactivity at a number of places throughout the world and the summary of several years of data is shown in Table 10 in Appendix B.[103] The radon concentration is inferred from the lead-214 measurements, since radon and its daughter products lead-214 are in radioactive equilibrium when the radon-laden air and dust coexist for 2 hours. The thoron concentration is inferred from measurements of lead-212. The thoron series has no long-lived daughters and its secular equilibrium is determined by the 10.6 hour half-life of lead-212.

The meteorological factors related to an air mass for several days prior to its observation influences its radon and thoron content. Both passage of the air over oceans and precipitation tend to reduce the concentration of these gases, whereas periods of temperature inversion cause them to increase. Washington, D.C., which is some distance from the ocean, had the highest thoron (lead-214) concentration of any coastal area studied, followed by seaports, midocean islands, and finally Antarctica.

Table 11 (Appendix B) shows the doses received by human beings throughout the United States from ionizing radiation that originates from cosmic rays and from gamma-emitting radionuclides in the earth's crust. The doses received in populated areas vary from 75 to 175 mrad/yr.[166]

Radiation emissions associated with the burning of fossil fuels are distributed generally throughout the country. The majority of the emissions will be concentrated in areas where large power plants are located. Therefore, the distribution of radioactive materials in the atmosphere from this source will follow distribution patterns similar to those of other fossil fuel combustion products (for example, sulfur dioxide).

3.2 Production Sources

The radioactive nuclides from production sources originate either as fission products or activation products; the ones encountered in atmospheric pollution are the same regardless of whether they are produced by nuclear reactor, a nuclear or thermonuclear bomb, or a plant reprocessing spent reactor fuel. The potential for radioactive contamination of the environment exists in all phases of processing radioactive materials. This processing involves mainly heavy industries, such as the uranium and thorium mines, metallurgical factories, nuclear reactors, and chemical plants.

Radioactive pollution of the atmosphere can occur by the release of airborne radioactive materials in routine industrial operations or as the consequence of an accidental release of airborne contaminants.

Nuclear reactor operations and nuclear spent fuel processing are the principal sources of radioactive gases. Those that are important in air pollution work, their main sources, and half-lives are given in Table 12 in Appendix B.

3.2.1 Production of Nuclear Fuel

The production of nuclear fuel for use in reactors or for nuclear explosions involves the mining of crude uranium or thorium ore, washing and concentrating the ore in processing plants adjacent to the mines, producing ingots of refined uranium or thorium, and physically separating the different isotopes of uranium and thorium. All these operations use only the naturally occurring radioactive elements belonging to the uranium and thorium families.

3.2.1.1 Mining, Milling, and Refining of Uranium

Uranium mining gives rise to the usual dust problems associated with conventional ore mining. The presence of radium in particles is not considered as important as the presence of radon gas daughter products. Adequate ventilation at the working faces of the mine must therefore be provided. The release of mine ventilation air to the atmosphere and subsequent dispersion provide large dilution factors.[154] In addition, mines are frequently in remote areas at significant distances from population centers. Therefore, this is mainly an occupational problem rather than a general air pollution problem.

Ore concentration begins with crushing and pulverizing the ore. These operations yield dusts containing a small concentration of radioactive materials, but the other toxic materials present (such as silica, vanadium, arsenic, and selenium) pose greater problems than the radioactive materials present. Adequate filtering of the ventilation air prevents the release of pollutants to the atmosphere.

The large tailing piles that have accumulated around uranium mills have recently become an area of public concern from the air pollution standpoint. It is feared that radon gas emanating from these piles may be an air pollution hazard to the general public in the surrounding areas. A joint study was made by the AEC and the Division of Radiological Health (now the Bureau of Radiological Health) to evaluate the atmospheric concentration of radon in areas near the piles as an index of radiation exposure of the population and to determine the effects of stabilizing and covering the piles on the emanation of radon gas. Piles at Durango and Grand Junction, Colo., and Salt Lake City and Monticello, Utah, were surveyed. The study has been completed but the results and conclusions have not been released.[11] Two States, Colorado and Wyoming, have passed legislation requiring covering of uranium tailing piles.[96]

The concentrates, consisting of impure U_3O_8 (pitchblende), are further processed for isolation and purification of uranium. Solvent extraction and fluoride volatilization are the principal methods used to produce pure compounds for reduction to metal or for the production of uranium hexafluoride, which is used in the gas diffusion process for producing uranium-235. The airborne radioactive products released from these processes are dilute, volatile uranium fluorides and uranium-containing dusts. During the feed preparation step, less than 3 μCi per day of uranium are released as the hexafluoride.[82] Uranium dust and other uranium compounds are controlled at the diffusion plants so that downwind concentrations are consistently less than the MPC.

Uranium ore processing plants are located in the States of Colorado, Utah, New Mexico, South Dakota, Texas, and Wyoming. Most of these locations are remote from populated areas. The milling plants are in general located close to the mines; these locations are shown in Table 13 in Appendix B. The location of plants refining the uranium ore concentrates to feedstock for fuel manufacture are shown in Table 14, Appendix B.

3.2.1.2 Fuel Fabrication

The fabrication of fuel elements for power reactors involves the metal-working processes of rolling, extruding, heat treating, machining, and cladding the uranium. Experience to date has shown that the potential for radioactive airborne pollution from these processes is minor.[154]

Since the development of the breeder reactors, there has been much interest in plutonium and plutonium alloy fuels. Plutonium metal is pyrophoric and extremely toxic; hence, great care must be exercised in its loading. To minimize the release of plutonium during fabrication, leak-tight enclosures are used for all work, and all exhaust gases are filtered at least twice through high-efficiency filters. Operating experience at Hanford, Oak Ridge, Argonne, and Los Alamos has shown that intricate operations with all forms of plutonium can be carried out without significant release of airborne plutonium.[94] Despite this fact, there have been some serious fires and explosions in plutonium-handling facilities; decontamination costs and equipment damage have been the most serious results.[80] No serious releases to the atmosphere have occurred.

From experience to date, the airborne radioactive contamination from uranium mining, milling, refining, and fuel fabrication processes is considered to be minor. In processing plutonium into fuels, great care is exercised in the design of equipment and control features to insure that negligible quantities are released to the atmosphere in day-to-day operations and in fires and other serious accidents.

The principal producers of uranium fuel for fabrication into fuel elements together with the locations of their processing plants, are shown in Table 15, Appendix B. Fuel fabrication plants are located in a number of areas throughout the United States. The locations of plants fabricating fuel for the nuclear industry are shown in Table 16 in Appendix B.

3.2.2 Nuclear Reactors

Nuclear fuels are introduced into reactors where heat is produced by nuclear fission. Radioactive wastes formed by nuclear fission are of two types: fission products, which remain incorporated in the nuclear fuels; and activation products, found mainly in the coolant. Both the fuel elements and the coolants are thus potential sources of radioactive atmospheric pollution. The pollution may come about through release into the atmosphere of radioactive gases, such as xenon and krypton (fission products); through the induced activity of atmospheric argon; through the formation of radioactive aerosols containing fuels (uranium, thorium, plutonium); through the release of fission products (strontium-90, cerium-144, barium-140, zirconium-95, and others); or through induced activity of other kinds.

The civilian nuclear power reactors (built for generation of electricity) operating at the present time are generally located around the Great Lakes and in the Eastern portion of the country. The new plants planned for the near future are concentrated in the same areas as well as in the Southeast, the upper Mississippi and Missouri regions, and the Pacific Coast. A list of the civilian nuclear plants—built, being constructed, and proposed—and the expected start-up dates are shown in Table 17, Appendix B.

In addition to the power reactors, a number of research and test reactors are located throughout the United States, as well as plutonium production reactors. The largest concentrations of test reactors are at the National Reactor Testing Station, Idaho Falls, Idaho, and Oak Ridge National Laboratories, Oak Ridge, Tenn.

Large plutonium production reactors are located at Hanford, Wash. and Aiken, S.C.

3.2.2.1 Normal Reactor Operation

The quantity and nature of the gaseous effluents will be influenced by the type of reactor used. The air-cooled reactor at Brookhaven Laboratories releases large quantities of argon-41, an isotope with a 112-minute half-life. Each operating day, some 14,000 Ci are released from a 300-foot stack.[170]

The waste gases released from the water reactors at Dresden 1, Big Rock Point, Humboldt Bay, Elk River, Yankee, and Indian Point 1 are shown in Table 18, Appendix B. Dresden 1, Big Rock Point, Humboldt Bay, and Elk River are boiling-water reactors; Yankee and Indian Point 1 are pressurized-water types. The power ratings of the stations vary from 24 Mw(e)* for Elk River to 200 Mw(e) for Dresden 1, and the periods of operation range from 4 to 7 years. All these plants have operated within the limits authorized by the AEC for release of radioactive wastes to the environment. The maximum annual average releases of gaseous activation products and noble gases have ranged from 22 Ci/yr (0.7 μCi/sec) at Yankee, to 35,000 μCi/sec at Big Rock Point.

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*Mw(e): megawatts electrical energy.

The releases varied from a maximum of 0.002 percent of the limit at Indian Point to as much as 28 percent of the limit at Humboldt Bay. Releases of halogens and particulates in the gaseous wastes ranged from 2×10^{-8} μCi/sec at Indian Point to nearly 1.2 μCi/sec at Big Rock Point, corresponding to about 0.00001 percent and 30 percent of the respective limits. The maximum annual average releases of 0.07 μCi/sec of halogens and particulates at Humboldt Bay corresponded to 38 percent of that station's licensed limit.[18,19]

The maximum off-site dosage measured above background at Humboldt Bay (integrated over 12 consecutive months) was only 50 mrems. Off-site air monitoring at other sites has yielded measurements at or very near the background level in all cases.[82]

Tritium is produced in nuclear reactors by fissioning of uranium, neutron capture in boron and lithium added to the coolant, neutron capture reaction with boron in control rods, activation of deuterium in water, and high energy capture reactions with structural materials. In light water reactors the main sources of tritium in the primary coolant are leaking of fission-produced tritium through cladding defects and boron and lithium reactions. In heavy water reactors, neutron activation of the deuterium moderator and coolant is the major source of tritium.[134]

The majority of the tritium released from the coolant reaches the environment as liquid waste. Only about 1 percent of the total tritium entering the atmosphere is released as gaseous waste.[194] Measurements made by the Bureau of Radiological Health's Nuclear Engineering Laboratory at a boiling water reactor indicate that the gaseous tritium release may be less than 0.5 Ci/yr.[134] Gaseous tritium releases from the Yankee pressurized-water reactor are reported to be less than 100 Ci/yr.[134] In heavy water reactors, only limited loss of heavy water can be tolerated for economy considerations, a consideration which effectively limits the release of tritium from this source. In addition, the rather high permissible concentration of tritium in ambient air also reduces this isotope's significance as an air pollutant from reactors.

Very short-lived nitrogen and oxygen isotopes are formed in large quantities from activation but do not pose an air pollution problem because of their rapid decay.

Several incidents in the past 20 years have occurred during fuel discharge of the Hanford reactors that resulted in temporary off-standard releases of airborne material. An estimated 4 Ci was released in one episode, yet only minor contamination was found in the environment. Filters and charcoal beds were installed in 1960, and since that time releases have been entirely insignificant.[114]

A serious incident occurred in 1958 at the NRU reactor, a heavy-water moderated Canadian experimental reactor, yet recovery was possible and only minor releases to the environment resulted. Due to a faulty mechanism, a highly irradiated fuel assembly was caught and could not be inserted into the discharge cask. A 3-foot portion melted and burned. A detectable level of contamination was found at a distance of 1,000 feet from the reactor building. Decontamination of the reactor required about three months.[87]

3.2.2.2 Reactor Accidents

Reactor accidents which result in melting of a large fraction of the highly irradiated fuel are highly unlikely—although credible. Upon melting, the core could release to the reactor building the noble gas fission isotopes and a fraction of the halogens and other volatile isotopes. The postulated accident which could cause this is called the design basis accident, and the reactor system is designed to preclude such an event. In addition, special designs (such as for a containment vessel) are required which "ensure" confinement or containment to a very high degree in the event of a serious accident. The AEC reviews all reactor designs prior to licensing to ensure the safety of the general public in case of an accident.

Some serious reactor accidents in the Western world have occurred in the United States, Canada, and England. The most recent of these, which resulted in the death of three military personnel, occurred in 1961 at the Army low-power (SL-1) reactor at the National Reactor Testing Station in Idaho. Through inadvertent withdrawal of a safety rod, the reactor went critical and the nuclear excursion resulted in a violent chemical explosion. Even though the reactor building was conventionally constructed, the radioactivity released from the core was substantially confined within the reactor building. An estimated 10 Ci of iodine (about twice the background radiation) was released and was detectable about 80 miles downwind.[55,184]

Through a series of compounding events in Canada at the NRX reactor in Chalk River, Ontario, a power surge melted about 10 percent of the uranium fuel rods in 1952. Some 10,000 Ci of fission products were carried below the reactor and spread through auxiliary equipment. Evacuation of the area for a weekend was required because of airborne gases.[72]

The only accident which caused any generalized environmental contamination occurred at Windscale, England, in 1957. The accident followed an attempt to anneal graphite by nuclear heat. The uranium elements in 150 fuel channels rose to such temperatures that cladding failed and the elements reached a glowing red heat. After carbon dioxide was found ineffectual, water was used to quench the uranium. The reactor cooling air was released to the atmosphere through a 410-foot stack, at the top of which was a low-efficiency filter. Some 20,000 Ci of iodine-131, 600 Ci of cesium-137, 80 Ci of strontium-89, and 9 Ci of strontium-90 were released. Milk was contaminated by iodine-131 in a 200-square-mile area to greater than the permissible level, and sale of milk from this area was forbidden for 3 to 6 weeks. The largest thyroid dose recorded among the inhabitants was 19 rad in one child. The reactor was never put back into operation.[182,197,198]

Even though the foregoing represent the worst accidents to date involving radioactive air pollution, the consequences in respect to air pollution were much less serious than some of the documented nonradioactive air pollution incidents on record.[168]

3.2.3 Fuel Reprocessing

The highly radioactive fuels taken from power reactors are reprocessed to separate the uranium and plutonium from the many curies of fission products. Many processes have been developed for removing the cladding material, dissolving the fuel, and extracting the uranium and plutonium.

Radioactive airborne contamination from a reprocessing plant is a potential problem, since all the highly radioactive fission products are released from the fuel during the dissolution step. Unless they are deliberately recovered, all noble gas isotopes in the fuel at the time of dissolution are swept out of the dissolver into the atmosphere. At present, krypton-85 releases do not constitute an air pollution problem. However, based on projected nuclear power expansion and population growth by the year 2060, it is estimated that the radiation dose from krypton-85 would be of the order of 50 mrad per year, and may be as high as 100 mrad per year. From the public health standpoint, 50 mrad per year may be acceptable if other sources of exposure are adequately controlled.[38]

Of greater concern at the present time is the potential for day-to-day emission of radioactive particles and volatile isotopes. The most critical volatile isotope is iodine-131, which can be reduced to negligible quantities by allowing a long storage time after the fuel is removed from the reactor. In addition, good processes are available for removing iodine-131 from exhaust air. Experience has shown that on a long-term basis and with adequate fuel-cooling and iodine-131 removal facilities, the routine iodine-131 emissions can be kept well below 1 Ci per day from a large separations plant.[109,114] Another isotope of iodine whose emissions from fuel reprocessing plants may be significant is iodine-129. Studies are in progress by the Bureau of Radiological Health to evaluate this problem.[193]

The fuel processing plants at Savannah River and at Hanford have experienced momentary releases of iodine-131 on occasion, due to equipment failure or inadvertent processing of fuel which had "cooled" less than 4 months. For example, the Savannah River Plant released 153 Ci of iodine-131 during a 5-day period in 1961.[109] The levels reached in the environment did not require withholding milk from consumption or any precautions other than monitoring action.

A very similar incident occurred at Hanford in September 1963[165] when about 60 Ci of iodine-131 were released. The maximum off-project grass level reached about 1.3×10^{-6} μCi/g. Increases in milk were detectable, but not dangerous.

Another isotope which forms volatile compounds is ruthenium, prominently present in the fission product mixture as ruthenium-103 (with a half-life of 40 days) and ruthenium-106 (with a half-life of 1 year). Ruthenium is relatively easily oxidized to the tetroxide, volatilized, and trapped in a caustic scrubber.[154] Radioactive particles are generated at almost every point in the process where a liquid is boiled, sprayed, agitated, or pumped. The very fine sprays may be carried out through the vessel vents or through very small leaks. The liquid evaporates, leaving a very small solid residue that carries with it the radioactive material. Very efficient filters are utilized for all air leaving the operation.

Isolation and purification of plutonium during fuel processing is accomplished through precipitation, fluorination, and eventual reduction to metal. Plutonium aerosols are generated from droplets and dry powders. Each enclosure where the work is performed is exhausted through a high-efficiency fire-resistant filter. The air is again filtered before release to the atmosphere through a tall stack.

The uranium stream from the fuel separations process becomes the feed for a calcining operation which converts the nitrate to oxide. The calcining yields airborne uranium oxide particles, practically all of which are retained on high-efficiency filters in the ventilation air exhaust.

Radioactive air pollution due to fuel reprocessing plants to date has been minor.[154]

The location of plants for reprocessing spent fuel removed from reactors is shown in Table 19 in Appendix B. The Nuclear Fuel Services Plant at West Valley, N.Y., is the only commercial fuel reprocessing plant in operation at present.

3.2.4 Nuclear Power Industry Projections

Until about 4 or 5 years ago, nuclear power for central power stations was essentially in a development stage. Since then, many utilities over a broad section of the country have decided to construct large power facilities based on nuclear heat sources because they are more economical than fossil fuels. In some borderline cases, the decision to go nuclear was made. Therefore, the growth of commercial nuclear-powered electrical generating facilities has been remarkable, with growth rates larger than had been predicted. In 1968 the new orders for a select group of nuclear products that are part of the nuclear power plants, as reported by the Census Bureau, exceeded 1.5 billion dollars.[129] The estimated growth of nuclear power plants is shown in Figure 1. The projected expenditures for construction investment are shown in Figure 2. A list of the commercial nuclear power plants already built, being constructed, and proposed for construction are shown in Table 17, Appendix B.

The projected market for fuel resulting from the growth of nuclear power is shown in Figure 3. This includes the total estimated cost of fuel from ore concentration to fuel fabrication. The cost for each step in the total fuel market for the year 1980 is shown in Table 20, Appendix B.

The overall use of nuclear energy, such as applications of radioisotopes and radiation, is expected to continue to expand. The market for radiation processing in 1967 was 250 million dollars, and it is expected to grow at the rate of 25 percent per year.[5] The projected 1968 market for radiochemicals and radiopharmaceuticals is 22 to 28 million dollars, with an annual projected growth rate of 25 percent.[129]

3.2.5 Nuclear Tests

Testing of nuclear explosives is another source of atmospheric pollution. The nuclear explosives are either based on fission processes employing uranium-235 or plutonium-239

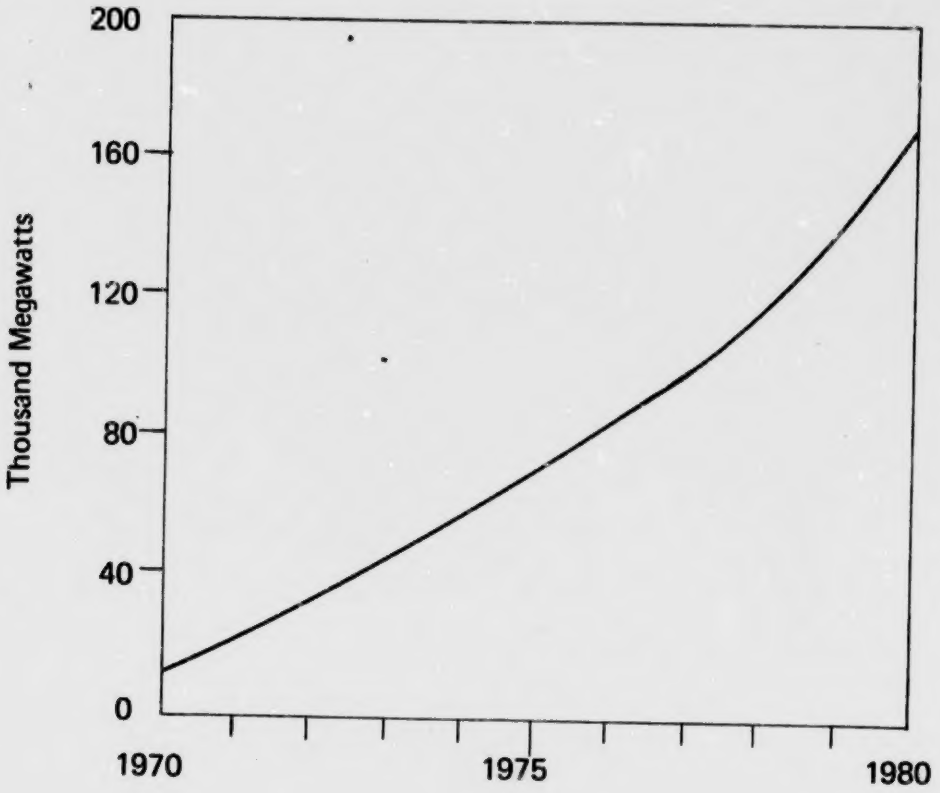

FIGURE 1

Estimated Capacity of Nuclear Power Plants[129]

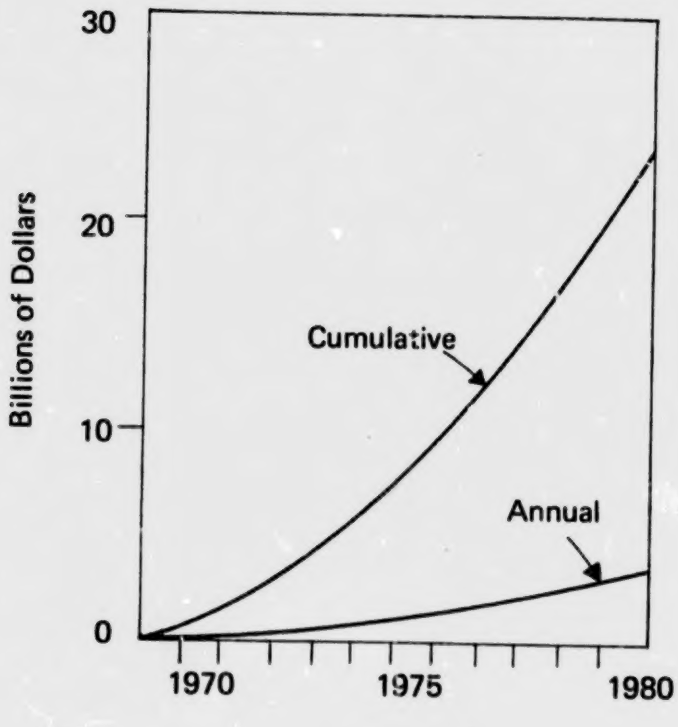

FIGURE 2

Projected Expenditures for Construction Investment[129]

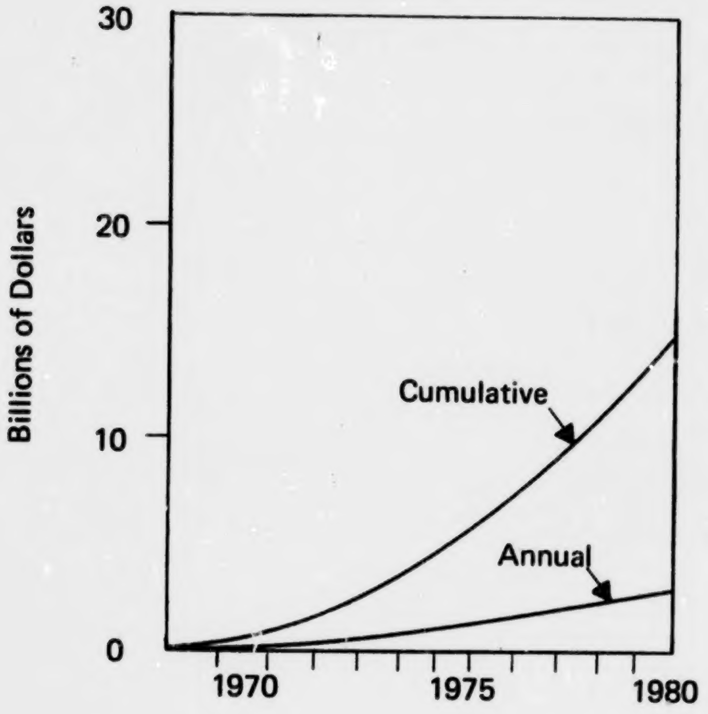

FIGURE 3

Fuel Cycle Costs[129]

or fusion reactions employing light nuclei (hydrogen or lithium).

The explosion takes the form of a nonmoderated chain reaction which produces large neutron fluxes that activate the surrounding material. The radioactive products released in a nuclear explosion are the fission products strontium-90, cesium-137, iodine-131, and others, and the activation products calcium-45 and sodium-24.[89] After some time has elapsed, the principal contaminants remaining are strontium-90 and cesium-137.[89]

The force of the explosion and the accompanying rise in temperature convert these radioactive materials into gases or else eject fine particles high into the atmosphere. The immediate result is thus a primary pollution of the atmosphere at the site of the explosion. This is followed by a secondary pollution due to radioactive fallout. The distance covered by the particles of radioactive material will vary with the height to which they are ejected and with their size. They will eventually settle out or be carried down by rain and become dispersed over the surface of the ground. In this way, pollution is produced at points remote from the site of the explosion, the distance depending upon the size of the explosion, the prevailing meteorological conditions, and the latitude at which ejection into the stratosphere takes place.[55] Examples of this remote type of pollution are illustrated in reports by Gold et al.[76] and Branson et al.[20] that reported on the measurements of fission product fallout in the United States from the Chinese nuclear tests in 1964 and 1965.

It is estimated that from World War II until the end of 1962, the total explosive yield of all nucelar detonations by the United States, the United Kingdom, and the Soviet Union was equivalent to 511 megatons of TNT, as shown in Table 21, Appendix B.

In 1963 a moratorium on open-air testing was adopted by the United States, the United Kingdom, and Russia. Since then, there has been a small amount of venting from underground tests conducted by the United States and Russia, but this has not added a significant amount of radioactivity to the total atmospheric inventory. Moreover, the Chinese and French have tested nuclear weapons, but these tests have not added appreciably to the radioactivity totals made prior to 1962.[147] During tests prior to 1963, it is estimated that about 30 percent of the radioactivity produced by the nuclear explosions was deposited in the immediate vicinity of the test sites.[168] Measurements of the atmospheric radioactivity resulting from nuclear weapons tests have been made at hundreds of locations throughout the world and at many elevations.[145] The measurements are contained in the reports of the United Nations Scientific Committee on the

Effects of Radiation.[145,146,147] The monthly mean concentrations of beta radioactivity measured in the United States following periods of major atmospheric nuclear testing are shown in Figure 4.

The hazard to man arises primarily from fallout since most of the debris is carried to the earth's surface in rainfall. The greatest source of human exposure is the radionuclides absorbed by man via the food chain (for example, the contamination of grass by iodine-131 fallout, with subsequent ingestion by cows and concentration in their milk).[168]

The majority of the radiation received from inhaled radioactive debris from weapons testing originated from zirconium-95 and cerium-144. During the heavy weapons testing in 1962 and 1963, doses to the lung amounted to only a few mrad per year, which is small in comparison with the normal background dose.[147] The total radiation from nuclear testing has added only about 10 to 15 percent to the normal natural radiation background dose.

3.3 Product Sources

Radionuclides are used as tracers in industry, biology, and agriculture and for internal irradiation in medicine. Another application of radionuclides is as sealed sources for gammagraphy and for massive external irradiation (sterilization). Radioactive wastes result only from the first type of application. These wastes may be either the

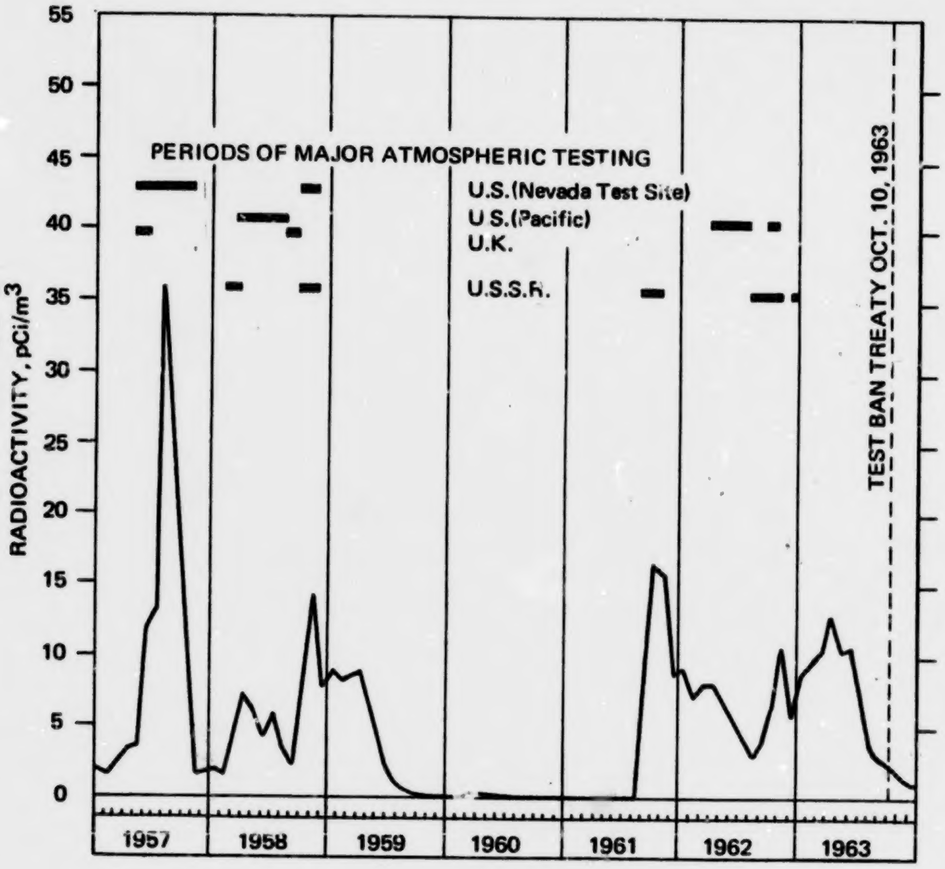

FIGURE 4

Monthly Mean Concentrations of Beta Radioactivity as Related to Testing of Nuclear Weapons[3] unused remains of the radionuclides employed, or products of transformation or excretion. The quantities involved are small, and atmospheric pollution from this source is generally of little significance.[89]

3.3.1 Aerospace Applications

A relatively new potential source of atmospheric pollution is the use of nuclear energy for rocket propulsion and as a source of power for satellites and space probes.

The first practical application of nuclear energy in outer space was the use of isotopic power units that produce electricity by thermoelectric conversion of the heat of radioactivity decay. The first isotopic power unit actually to fly in outer space was a 2.7-watt generator containing 80-year plutonium-238. This unit powered the communications system in TRANSIT, a communications satellite designed to provide constant frequency transmission for a period of several years. This device was placed in orbit in June 1962.[168]

In April 1964, an isotopic power device containing plutonium-238 burned up at about 150,000 feet over the Indian Ocean during reentry into the atmosphere. Traces of the plutonium-238 were found at the expected altitude and latitude, confirming the belief that complete burnup was achieved. The material is slowly descending toward the ground and has recently been detected in the surface air. It is expected that this will give rise to a negligible amount of air pollution.[147] Although these types of nuclear energy uses are new potential sources of atmospheric contamination, it seems unlikely that in the foreseeable future the levels of atmospheric contamination will approach those to which the world was once subjected as a result of nuclear weapons tests.

The United States is engaged in the development of a rocket propulsion system utilizing nuclear power. For some years this program will be in an experimental stage which will limit the operation of reactors to land-based test units at remote locations, such as the Nevada Test Site. Because of the isolation of the test units and the relative infrequency of test firings, it is not likely that the nuclear rocket program will constitute a significant source of atmospheric pollution for some years.[168]

3.4 Other Sources

Other sources of radioactivity are pilot plants, research laboratories, and laundries ~~for washing~~ contaminated clothes, as well as metallurgical examination of fuels, and incineration of slightly contaminated clothing and radioactivity filters. In such cases, the release of particulate activity is easily controlled by absolute filtration of all air from active laboratories; the levels of gaseous activity are invariably so low that no significant air pollution occurs.

Another potential source of radioactivity can result from the peaceful use of nuclear explosions underground to stimulate gas production, provide gas storage basins, enhance the production of oil from oil shale, and facilitate solution mining of copper. Many.such projects have been proposed or are in the planning stages. (Table 22, Appendix B). One project, called Gas Buggy, was conducted in December 1967, to stimulate gas production. The results of this project are being evaluated. The potential for release of radioactivity accurs mainly during the production and use of the end products; for example, fuel gases produced or stored can become contaminated with radioactive materials that are released when the gas is burned. To minimize the possibility of such contamination, the area is not used for a period of time afterwards to allow the radioactivity produced during the explosion to decay.

3.5 Environmental Air Concentrations

Prior to 1967, sampling for gross beta reactivity was carried out at 323 stations throughout the country by the Air Surveillance Network of the National Air Surveillance Networks Section, Division of Air Quality and Emission Data, Bureau of Criteria and Standards, National Air Pollution Control Administration. Since 1967 the Air Surveillance Network has limited its radioactivity sampling to the West Coast.[123] The Radiation Surveillance Network (RSN)—which in 1967 became the Radiation Alert Network (RAN) of the

Radiological Surveillance Branch of the Division of Environmental Radiation, Bureau of Environmental Health—samples the atmosphere for gross beta activity at 74 stations throughout the country. The network is oriented toward detecting radioactive fallout from weapons testing.[8] Therefore, if the atmospheric radioactivity exceeds 10 pCi/m^3 (or 5 pCi/m^3 in Hawaii, Alaska, and Puerto Rico), the samples are scanned for fission products. Data from the Radiation Alert Network are published each month in the Radiological Health and Data Reports. In the near future, the Radiation Alert Network is expected to become part of the Air Surveillance Network.[123]

Lockhart and Patterson[104] intercalibrated the Radiation Surveillance Network (RSN) and the Air Surveillance Network (ASN) by sampling for beta activity at the Naval Research Laboratory in Washington, D.C., utilizing the systems and methods used by these networks. The samples were then counted at the Naval Research Laboratory and at the Network laboratories, utilizing their standard procedures. They found from these data that the RSN measurements were lower than the corresponding ASN measurements, primarily due to the different type of filter paper used by the two systems. The RSN uses carbon-impregnated cellulose paper, which allows a greater penetration of radioactive particles than does the glass-fiber filter paper used by ASN. The relative activity concentration or intercomparison factors for the two systems are

$$\text{RSN} = 1.00, \text{ ASN} = 1.77$$

Gross beta measurements made by the ASN for the years 1953 to 1966[2] are shown in Table 23, Appendix B.

4. ABATEMENT

Radiation cannot be detected without special instrumentation, and the biological effects are usually not evident until some time after exposure. Therefore, reliance must be placed on methods for preventing the atmospheric activity from exceeding permissible levels. The abatement systems and methods utilized to prevent atmospheric pollution are rigorous, systematic, and organized so as to provide multiple and successive safeguards. In addition, the abatement systems must be designed to handle not only pollution arising out of normal working conditions, but also the accidental pollution caused by defective installations or faulty operations.

Effective control of radioactive pollution consists of limiting the emission of radioactive pollutants, containing them to prevent the spread of the pollution, and dispersing them to reduce the pollution below the maximum permissible level.

4.1 Control of Radioactive Pollution

4.1.1 Limitation of the Emission of Radioactive Pollutants

There is often a choice of techniques for carrying out a mining or processing operation, some of which offer special advantages for limiting air pollution. In uranium mines, for example, pollution can be kept to a minimum by the use of wet drilling, by underground drainage, and by clearing away the ore as rapidly as possible to prevent the release of radon. In nuclear reactors, the risk of pollution can be reduced by using closed-cycle coolant systems and maintaining high coolant purity to minimize activation products. In addition, nuclear testing can be carried out under meteorological conditions chosen to ensure minimum dispersal.

4.1.2 Containment

Containment of radioactivity can be done in two ways: the polluted atmosphere itself can be contained, or the radioactive pollutant can be contained by not allowing it to escape to the atmosphere. In the first case, the polluted air is separated from the air where people are working or from the outside atmosphere. A reactor containment building serves to minimize the release of fission products to the outside atmosphere if an accident allows them to escape from the reactor. In the second case, the radioactive gases are completely contained by means of hermetically sealed tanks and closed-cycle process systems.

4.1.3 Dispersal

The dispersal method consists merely of diluting the pollution with a volume of air large enough to reduce the resulting concentration of radioactivity in the air below maximum permissible concentrations.

Radioactive pollutants are dispersed by means of stacks. The satisfactory dispersal of radioactive gas to the atmosphere at permissible concentrations depends upon the position, height, and discharge of the stack and on local meteorological factors.

4.2 Location of Facility Site

A guiding principle in locating an atomic facility is to select a site where the possibility of excessive radiation doses to the general public will be minimized.[33,35-37] In choosing a site, the most important considerations are

(1) The type of installation (i.e., nuclear reactor, chemical treatment plant, plutonium extraction center, etc.), since it will influence the type of accident most likely to occur and the consequences of an accidental release of radioactivity.

(2) The area's meteorological factors, especially the local weather conditions, prevailing winds, rainfall pattern, temperature changes, humidity, and others.

(3) The nature of the environment likely to be contaminated; i.e., distribution of the population, position of industrial and residential areas and of agricultural zones, and other factors.

4.3 Air Cleaning Methods

Airborne radioactive particulates and gaseous substances are produced in many of the operations in the nuclear energy industry. Since some of these are produced at levels that preclude direct release to the environment, a variety of methods have been used for their collection and removal prior to release. These methods include filtration, centrifugal collection, wet collection, electrostatic collection, surface absorption, and delay to allow for decay. The air cleaning method utilized will depend upon the form of the radioactive material (particulate or gas), the particle size, and the chemical and physical properties of the atmosphere and its contaminants. Tables 24 and 25, Appendix B. show the methods used to remove radioactivity and their efficiency.[159]

4.3.1 Radioactive Particulates

Radioactive particulates consist of dust, fumes, smokes, and mists and range in size from less than 0.05 μ upward. The degree of removal required for radioactive particulates is considerably higher than that encountered in normal (nonradioactive) industry practice. Removal efficiencies of 99 percent or better are required in many instances for particles of less than one μ in diameter. These removal efficiencies have been achieved by conventional methods or by refinements of them.

Filtration[6,114,137,170] is the most widely used method of removing radioactive materials from air. Filtration equipment can consist of roughing filters, absolute filters, bag filters, deep-bed sand filters, or combinations of these, depending upon the dust loading in the air and the removal efficiencies required. Absolute filters give removal efficiencies of better than 99 percent for particles greater than 0.3 μ. For high dust loading situations, absolute filters are often preceded by coarser filters. These can consist of roughing filters, bag filters, or deep bed filters.

Electrostatic precipitators[158,170,171] and cyclones can also be used in high dust loading situations. However, electrostatic precipitators are rarely used because of their high cost. Small cyclones[6,170,171] have been used in collecting swarf from uranium machining operations, and large cyclones[6,170,171] have been used in ore operations.

4.3.2 Wet Collection

Mixed aerosols such as acid mists and solids are usually removed by wet collectors. This group of equipment consists of wet filters, viscous filters, packed towers, cyclone scrubbers, and venting scrubbers. As a class, scrubbers will rarely remove particles less than 0.5 μ in diameter. They cool as well as clean the gas. The removal of dust is continuous, but the relatively large quantities of liquid effluent may require treatment as liquid radioactive wastes. There may also be a danger of chemical reaction between fine metallic dusts and water.[6,170,171]

Wet filters have been used in the absorption of acid mists and vapors from laboratory fume hoods, particularly when hydrofluoric and perchloric acid mists were present.

Viscous filters are primarily used as prefilters for general ventilation air.

Packed towers or spray columns are particularly useful when the aerosol contains some reactive chemical. However, they are mainly used for gas absorption rather than air cleaning.

Cyclone scrubbers are used where removal of pyrophoric materials are necessary. Venturi scrubbers are often incorporated in the air-cleaning train of incinerators, since they allow high gas temperatures to be handled.[6,170,171]

4.4 Radioactive Gases and Vapors

During reactor operation, volatile radioactive gases and vapors are formed that cannot be removed from air or other carrier gas streams by filtration. The most dangerous of these are the isotopes of iodine (^{131}I and ^{133}I) and the isotopes of krypton and xenon (^{87}Kr, ^{88}Kr, ^{133}Xe, ^{135}Xe, and ^{85}Kr).

It is extremely difficult and expensive to remove small quantities of radioactive inert gases from large volumes of air. Therefore, in most cases it is easier and simpler to install waste gas treatment systems to treat the gases prior to release to the ventilation system.

The methods available for removal of radioactive gases are absorption and chemisorption, adsorption, and storage until the isotope has decayed.

4.4.1 Chemisorption and Adsorption

The adsorbents used for removing radioactive gases and vapors include activated carbons, silica gels (pure or impregnated with chemicals which give them chemisorptive properties), and chemicals based on soda lime (to absorb acidic vapors and gases). Other substances used include those having a selective adsorption capacity for certain types of material, for example, silver and its salts or oxide plated on inert carriers such as unfired porcelain and Alundum, aluminum oxide, or metal mesh and finely-ground metals.[1,22,137,170,171]

The activated carbons are efficient and cheap and will remove many radioactive vapors and gases from air and other carrier gas streams. At low temperatures, they are good adsorbents of radioactive inert gases such as xenon and krypton. The silica gels are used to decontaminate gases containing high concentrations of oxidants, but not fluoride or hydrogen fluoride. The adsorbents based on soda lime are used as alkaline chemical absorbers for acid gases and vapors (compounds of iodine, phosphorus, and carbon dioxide). Selective adsorbents—such as silver plate on activated carbon, silica gel, or nonporous material (porcelain)—are highly efficient for the decontaminating streams containing radioactive iodine.[22,137]

4.4.2 Absorption

Absorption is suitable for removing from the ventilation air gases that react chemically with the scrubbing liquid or are highly soluble in it. Normally, this method is used for the relatively gross cleaning of the air of (inorganic) compounds of radioactive iodine, carbon-14 dioxide, and others.[6,171]

The most important absorbents for removing radioactive contamination from the air are

(1) Water (although not always sufficiently effective, such as in removing iodine from air), and

(2) A weak alkaline solution (pH 8 to 10) the most widely used absorbent.

The same equipment is used for air cleaning by absorption as is used for the removal of dust and aerosols from air. However, the efficiency of even the best installations of this type is not great, and removal does not usually exceed 90 to 95 percent.

The main disadvantage of this type of equipment is that it produces radioactive waste water.

4.4.3 Delay in Storage

The delay or retention of gases in tanks until the radioisotopes have decayed enough to permit release is one of the simplest and most reliable ways of removing radioactive inert gases—argon, krypton, and xenon—from the air and other carrier gases. In order to reduce the activity of a given isotope by a factor of 100, the retention time must be 6.7 times the half-life of the isotope; and for a thousand fold reduction, the retention time must be 10 times the half-life.[18,19,171]

The delay in storage method is used primarily for the removal of comparatively short-lived isotopes, especially radioactive inert gases, from limited volumes of air and other carrier gases. However, storage tanks can also be used for temporary storage of exhaust gases during unfavorable meteorological conditions, such as inversion or unfavorable wind direction. The gases are stored until the meteorological conditions are satisfactory and then released.[18,19]

5. ECONOMICS

In the last few years the growth of the commercial nuclear power generating industry has been greater than had been predicted even 5 years ago. (See Section 3 for projected growth rates). Each nuclear facility must incorporate safety systems that will safeguard the public from uncontrolled and excessive release of radioactive materials to the atmosphere. It has been estimated by Vann[186] that the costs associated with reactor safety for plants being engineered and constructed for mid-1973 service constitute approximately 10 percent of the total plant cost. For a 800 Mw(e) light water reactor plant this would amount to about $18,000,000.[186] This figure includes costs of components, piping, structures, and engineering.

A cost analysis of the dust collectors used at AEC facilities to prevent release of toxic and radioactive dusts to the atmosphere was made by First and Silverman.[68] From their study they determined the following costs for air cleaning equipment:

(1) For air supply units of 10,000 cfm capacity, dry fiber throwaway prefilters cost under $50/1,000 cfm/yr; two-stage electrostatic precipitators cost $76/1,000 cfm/yr.

(2) For exhaust air cleaners of 10,000 cfm capacity, most dry and wet medium-efficiency mechanical dust collectors will cost approximately $50/1,000 cfm/yr, and cleanable

fabric dust collectors will cost about twice this amount.

(3) The costs and service conditions of some dry mechanical and wet dust collectors installed at the AEC facilities are shown in Tables 26 and 27 in Appendix B.

The economic impact of radioactive air pollution on humans, animals, and plants is expected to be minimal at the low levels presently encountered. Some economic losses have been incurred in the past from accidental releases of radioactive materials from nuclear facilities such as in 1957 at Windscale, England, where contaminated milk was withheld from the market.

The main impact of radioactive pollution is in the area of long-term health effects, and the magnitude of this impact is not yet known. Potential releases of krypton-85 from an expanding nuclear industry could well limit nuclear expansion around the year 2000 if it is determined that the radiation dose from the quantity of krypton-85 released at that time is harmful to health.

6. METHODS OF ANALYSIS

Radioactive materials are produced and dispersed in a variety of ways. In most cases, the radioactive pollutants occur as solid particles dispersed in air. They rarely occur dispersed in air as liquids. However, some of the products are gaseous such as radon, elemental radioiodine and some of its organic compounds, radiocarbon as carbon dioxide, and radioargon. The method of sampling and monitoring for radioactive material dispersed in air depends on the physical form of the material. Techniques for measuring radiation have been developed which are sensitive to extremely minute amounts. As a result, the amounts of radioactive material that can be detected and measured quantitatively with a high degree of accuracy are much smaller than almost any other atmospheric pollutant.

6.1 Sampling Methods

The types of collecting devices used to sample radioactive particulates are filters, impactors, impingers, and settling trays. Large particles can be collected on settling trays. However, sampling for radioactive particulates is usually accomplished by pulling the air at a measured flow rate through the collecting device.[1,46,102,168]

6.1.1 Filters

Filtration through paper is the most widely used technique for sampling radioactive particulates.[119] The types of filter paper used by some various air sampling networks throughout the world have been listed by Lockhart *et al.*[105] They have listed cellulose, cellulose-asbestos, cellulose-glass fiber, glass fiber, polystyrene, and membrane filters. Glass filters are probably used more extensively than the other filter types. However, certain inherent advantages are obtained from using other filter media. For example, the synthetic organic filters and cellulose filters are easily burned and essentially ash-free, where the glass and asbestos filters leave a residual ash when burned. This may be an advantage during analysis because of the presence of a finite amount of material for observation and manipulation. Chemical processes are available to dissolve the ash from the glass or asbestos filters or to dissolve the filter media without ashing.

The membrane-type filters are readily soluble in a wide variety of organic solvents, and they can easily be ashed. Thus, when chemical operations are to be performed on the collected dust, the dust can be easily separated from the filter. In addition, a drop of the proper immersion oil in contact with a filter on a microscope slide makes the filter completely transparent for microscopic examination of collected material.[149] Techniques have been developed for transferring collected material from membrane filters to electron microscope grids so that very small particles may be observed.[93]

Where direct counting of the filter media is to be used to measure the collected radioactivity, radioactive particle penetration of the filter paper should be minimized; highly compacted filters which are essentially surface collectors should be utilized. Lockhart _et al._[105] have made measurements on penetration of various filter media by smoke.

Collection efficiencies of 100 percent in a sampling system are not necessary provided the efficiencies are at least 90 percent and are known for the material to be collected. Lockhart _et al._[105] have listed measurements made on collection efficiencies of various filter media for natural radioactive aerosols and airborne fission products.

6.1.2 Impactors

In impactors the airstream is speeded up by a jet and then impinged or impacted on a surface coated with a sticky material to catch the dust. The material is collected in a small area immediately in front of the jet and the size range collected is a function of the jet velocity and the system dimensions. Impactors are rarely used for pollution monitoring involving radioactive materials because of the long collection times required under outdoor conditions where natural dust exists. Moving slides and tapes have been used for this purpose but are only satisfactory for relatively short periods of sampling.[168] The Anderson sampler (although an impactor similar to the cascade impactor) collects more material and more fractions. This impactor consists of a series of perforated plates and collecting plates. The air is forced through a perforated plate onto a collecting plate, where the fraction is collected.[168]

6.1.3 Impingers

Impingers use impaction under a liquid surface and are rarely used in air pollution studies. They occasionally have been used for sampling stacks emitting hot, wet gases. The impinger may be immersed in ice water for this purpose and the aerosol then trapped in the liquid.[168]

6.1.4 Settling Trays

Settling trays are widely used in air pollution work and have been used for radioactive materials. The "fallout tray" is a standard instrument in radioactive air pollution monitoring. The tray is a metal sheet coated with a sticky material or lined with sheets of gummed paper.[89,168]

After exposure, the metal sheet can be placed in a counter for direct counting of radioactivity, or the material can be removed from the tray and the radioactivity determined. The collected material can be washed off with a solvent and the material wet- or dry-ashed for analysis. After exposure, gummed paper can be stripped off and ashed out. Radiochemical analyses for various elements can then be performed.

Another method of evaluation is by autoradiography of the tray. The sticky surface is covered with a thin plastic sheet, placed in contact with a sheet of X-ray film, and kept in the dark for a fixed period. After development of the film, the dark spots reveal the presence of radioactive particles, which can then be evaluated.[161] Instead of sticky trays, a shallow tray filled with water can also be used. The water can then be evaporated or filtered for direct counting.

Radioactive washout by precipitation is evaluated by collecting precipitation in stainless steel trays. The water is then evaporated and the residue is counted for radioactivity.

6.2 Quantitative Methods

6.2.1 Analysis of Collected Particulate Samples for Activity

Direct radioactive counting of filter paper and other samples involves considerable electronic equipment. The size of the probe or counting chamber should match that of the collection medium, which usually is filter paper. Special probes that can be used with standard scalers or count-rate meters are built to handle most filter paper sizes.[89,168]

Proportional counters are widely used for activity analysis but can give erratic results with filter papers because the filter paper, being an insulator, distorts the electric field in the counting chamber. Scintillation counters are more widely used at present for counting all types of air samples than proportional counters. For alpha counting, the scintillation surface is placed very close to the filter. Low-level radioactivity can be counted, using small disks of scintillating material on clear plastic placed in actual contact with the deposited material. The counting device is a photomultiplier which "sees" the light flashes inside a scintillating medium.[79]

Gamma activity is usually counted with a crystal as a scintillator although Geiger tubes with end windows have been used. Beta counting can be done with scintillating crystals (or powders) on plastic films or with thin window proportional counters. Multichannel analyzers are used, particularly with gamma emitters, to give qualitative information on the isotopes present. As noted previously, membrane filters are best for collecting alpha emitters. These are then counted with solid-state detectors connected to a multichannel analyzer.

The air usually contains appreciable quantities of naturally occurring radioactive particulates. These particulates are collected on filter paper at the same time that other radioactive contamination is being measured. If the samples are counted immediately after the end of the sampling period, the results are high because of the presence of these short-lived natural radioactive materials. Counting can be delayed for several days to permit the decay of the natural products or several counts can be made and a correction calculated.

Combined sampler-counter units are available that use a scintillation counter probe placed near the filter paper during the sampling period. The counter used is a count-rate instrument and the output is connected to a recorder, which then measures the buildup of activity on the filter paper. These types of instruments are rarely used, however, for monitoring alpha emitters. Instruments also have been built using filter tape—moving intermittently or continuously—as a collector so that one sample is counted while another is being collected.[70,83]

6.2.2 Radioactive Particle Size Analysis

The mass concentration of a radioactive contaminant in air usually is so minute, even at concentrations above permissible levels, that it cannot be seen on the collection media. Therefore, it is seldom possible to use optical techniques. The concentration of ordinary dust is always much greater than that of the radioactive dust. In addition, there is seldom any visible characteristic of the radioactive dust by which it can be distinguished under the microscope. Therefore, indirect sizing methods usually are used.

A widely used indirect method for sizing uses the cascade impactor. This instrument draws air through a series of progressively smaller jets. After each jet, the nuclear track film, which is then developed. When the film is examined under a microscope, tracks can be seen where alpha particles were emitted, and the number of tracks emanating from a single point is a measure of the amount of radioactive material in the particle at that point. From the calculated mass of material, the particle size can be estimated.[97]

6.2.3 Gases

Radioactive gases require special handling for analysis depending on their chemical and physical properties.

6.2.3.1 Iodine

Iodine is collected on activated charcoal,[70] although chemical absorbers also have been used. The samples collected can then be analyzed by placing the absorber directly on a scintillation crystal or in a well counter for gamma counting. By using discriminator circuits in a gated single-channel analyzer, a high degree of sensitivity can be obtained.

When the iodine is completely gaseous and entirely in elemental form, the charcoal absorption method gives reliable results. At ordinary temperatures, however, some iodine may be present as solid particles, or atoms may attach themselves to other solids in the atmosphere. Such materials can penetrate the absorbent. For this reason, filter paper is usually placed in front of or behind the collection cartridge during air sampling. Both should be counted when air is allowed to impact on a plate coated with an adhesive or dust-retaining material. Since the jet velocities increase as the jet size decreases, progressively smaller particles are impacted and retained. If the impactor has been properly calibrated, the size ranges deposited on each stage will be known;[7,168] and if the cascade impactor has been properly calibrated using an aerosol similar to the one being sampled, it is fairly accurate. Particle shape, density, and size affect the stage constants. Other errors may be introduced by leakage of air into various parts of the impactor, by deposition inside the instrument body, and by resuspension of deposited aerosol from heavily loaded slides.

There are several aerosol spectrometers that can be adapted for use with radioactive materials. In Timbrell's aerosol spectrometer, the air passes horizontally in a thin film above a long surface and the particles settle on the surface. Since the larger the particle, the sooner it settles, the distance that the particle is located from the entrance is a measure of the particle size, and the amount settled out at various distances can be measured to give the size distribution.[180] This system, satisfactory only for particles larger than 10 microns, is seldom used for air pollution work.

In the Conifuge, centrifugal force is used to speed up the settling. The aerosol-laden air is passed through hollow space between two cones which are rotating rapidly.[153] Therefore, the particles are driven to the outside wall, where they are deposited on an adhesive-coated surface. Distance down the wall from the entrance is again a measure of size. This instrument is expensive, difficult to build, and primarily used in laboratories.

Another laboratory instrument, the Goetz aerosol spectrometer,[75] is similar to the Conifuge but the air traverses a spiral down the annular space between the cones. The air is not guided into the deposition space in a thin layer and therefore, the distance from the entrance is only a measure of the maximum size particle deposited there. Interpretation of the resulting data is quite complex.

Other methods for sizing radioactive particles depend upon placing the collected sample in contact with film for some time, developing the film, and examining it under a microscope. The particle can be left in place during development or the film can be developed separately and then placed in contact with the particles again. When examined under the microscope, the radioactive particles can be identified by the darkened spots under the particles on the film and can then be sized.

For measuring alpha-emitting particles, the collected aerosol is placed in contact for a period of time with a measuring the iodine concentration.

Some iodine has been found to penetrate various absorbents and filters. There appear to be several compounds of iodine having different diffusion characteristics.[23,177] Some materials such as silver-coated copper mesh have been used as traps for iodine, and their efficiency seems to be dependent on humidity. Silver-coated filter papers and charcoal-loaded filter papers give high efficiencies with iodine formed in the laboratory, but varying efficiencies with iodine produced by reactors or industrial fuel-processing operations.[58] Scrubbers containing sodium hydroxide can also be used in sampling air for iodine.[164]

6.2.3.2 Tritium

Tritium is usually present in the form of gaseous molecular hydrogen or as water vapor. When dispersed in air as molecular hydrogen, it gradually oxidizes to tritium oxide or water as a result of self-activation. Ambient tritium consists mainly of water vapor (HTO).[196]

Low-level counting of tritium can be conveniently and accurately accomplished by liquid scintillation counting systems. Tritium samples are collected from the air by freezing out the water vapor from the air with a cold trap, then melting the collected sample. Water is then mixed with liquid scintillation solution. The mixture is then counted by a liquid scintillation counter. All operations involving the scintillation solution are performed under red light to avoid phosphorescence resulting from excitation of the scintillation solution by white light.[121]

6.2.3.3 Noble Gases

The usual method of monitoring for noble gases such as argon-41, krypton-85, xenon-133 and xenon-135 is by means of a simple thin-window Geiger counter in the atmosphere. The Kanne chamber or other ion chamber can also be used. For measurement of very low concentrations of xenon and krypton, a charcoal-freeze-out pump is used for trapping the gases, which can then be released into an ion chamber or a chamber containing a Geiger tube for measurement. Since permissible air concentrations of these gases are relatively high, such techniques are rarely required.[168,177]

6.2.3.4 Other Radioactive Gases

Gas such as carbon-14 dioxide and sulfur-35 dioxide may be formed as a result of operations in an isotope laboratory or through incineration of radioactive wastes. These gases are sampled by liquid scrubbers containing sodium hydroxide or barium chloride with an oxidant. The determination of collected radioactive material is easily made by liquid scintillation counting. The precipitated barium carbonate or barium sulfate also can be filtered off and the filter paper counted in a suitable instrument, or a sniffer can be used for determining the gas directly.[168]

Oxygen and nitrogen can become radioactive if exposed to intense radiation. The half-lives of these irradiated materials are short; therefore, they are not an air pollution hazard. Unshielded Geiger counters or other detectors can be used for direct measurements of radiation where this is necessary.

When reactor fuel elements are dissolved in highly oxidizing solutions, ruthenium, which is formed by the fission process, may be oxidized to the volatile tetroxide and released. Ruthenium-106 is the most hazardous isotope of this element. Air containing ruthenium can be sampled by passing it through an absorber containing a dry organic material such as polyethylene pellets, and the ruthenium content determined by gamma counting.[89,168]

6.2.4 Air Quality Monitoring

Generally, monitoring for radioactive substances is done in much the same way as for nonradioactive materials. Sampling locations are determined both by meteorological and demographic factors and the specific information to be obtained. Although airplanes, rockets, and high-altitude balloons are all employed in measuring radioactive fallout, the sampling equipment for each uses the same principles. Since such pollutants are widely distributed, exact sampling locations are not critical.[89,168,175]

Duration and frequency of sampling are also similar to those employed in all air pollution work. In some cases, sampling times must be limited because of the short half-life of the pollutant being measured. The high sensitivity of radioactivity measurements and the ready conversion of the radioactive emissions to electronic pulses make continuous monitoring possible in most cases.

Continuous monitoring of reactor installations is effected by a chain of stations suitably arranged around the site. Many different techniques and types of equipment are utilized at various facilities throughout the country. The Division of Radiological Health is reviewing the monitoring techniques and equipment used at the present time with the intention of developing uniform measurement techniques.[193] One method presently used at many facilities to measure radioactivity in air is to pass the air through a tape of filter paper that is continuously fed to a discharge or scintillation counter. Ionization chambers and filter detectors give instantaneous information on pollution with radioactive gases and dusts. When used in conjunction with recording equipment, they enable the average pollution at the measurement point to be determined; when fitted with alarm devices, they can give a warning if the maximum permissible concentrations are exceeded.

7. SUMMARY AND CONCLUSIONS

Radiation has been observed to produce somatic effects such as leukemia; lung, skin, thyroid, and bone cancer; cataracts; and life-span shortening. In addition, it is responsible for significant genetic effects. Although some estimates of the dose-time relationships to these effects have been reported, there is some uncertainty in safe levels of exposure to radiation.

There is at present a generally wide acceptance of the biological concept which holds that there is no level of radiation exposure below which there can be absolute certainty that harmful effects will not occur to at least a few individuals. This concept is based to a large extent on considerations of potentially harmful genetic effects. While many of the acute and long-term biological effects of high doses of radiation are known, there is a lack of information on the biological effect of low doses and low-dose rates of radiation. In general, somatic effects are less likely to occur at low-dose rates. Much more information is required to fill the information gaps in the area of low doses and low-dose rates, which are of primary concern in air pollution.

Animals suffer effects similar to those observed in man, and all of the effects observed in man have been confirmed with experimental animals.

Plants are suspected of undergoing genetic mutations. However, the experiments have been carried out at radiation doses far in excess of those encountered in ambient air. No material damage has been observed by the radiation found in ambient air.

On the basis of recommendations from the International Commission on Radiological Protection (ICRP), the National Committee on Radiation Protection (NCRP), and the Federal Radiation Council (FRC), the AEC has established standards of maximum permissible concentrations (MPC) of nuclides that can be released from nuclear plants.

The nuclear industry has expanded rapidly in the past decade and will continue to expand. With this rapid expansion, there has been an increase in potential radioactive pollution of the atmosphere. Experience to date has shown that the radiation dose to the general public from nuclear plant emissions has been insignificant when compared with that from natural radioactivity. The dose to the population from nuclear weapons testing was more significant, amounting to levels about 5 to 10 percent higher than the levels of natural radioactivity.

Recent investigations have indicated that krypton-85 releases from fuel processing may add significantly to the general public radiation dose rate (50 to 100 mrad/yr) by the year 2060. Krypton-85 is a radioactive gas with a long half-life and at the present time is vented to the atmosphere. Methods must be developed for preventing the release of this noble gas.

The projected growth of the nuclear industry in localized areas (such as near Lake Michigan) may in the future produce higher than desired radiation levels in the local air basin. The total emissions from these concentrated facilities may be excessive, even though the emissions from each new facility alone are well within their discharge limits. This problem will require careful review in the future.

Fossil fuels contain natural radionuclides that are released from the fuel by combustion. Therefore, radioactivity is released from fossil-fuel-fired power plants that in some cases can amount to more than that released from a similar-sized nuclear power plant.

Accidents have occurred in the nuclear industry, and in some cases resulting in releases of appreciable amounts of radioactivity. In other instances, the result has been temporary atmospheric pollution. Most of these incidents were caused by human error rather than the failure or inadequacy of the air cleaning systems.

Environmental radiation monitoring programs are conducted by State, local, and Federal agencies external to the nuclear facility site perimeter to monitor radioactivity releases. In addition, the Radiological Surveillance Branch, Division of Environmental Radiation, Bureau of Environmental Health, has a National Surveillance Network (Radiation Alert Network) to monitor environmental radioactivity. However, this network is oriented toward detecting radioactive fallout from weapons testing. In the near future, the Radiation Alert Network is expected to become part of the Air Surveillance Network of the National Air Surveillance Network Section, Division of Air Quality and Emission Data, Bureau of Criteria and Standards, National Air Pollution Control Administration.

The low levels of radioactivity from all phases of the nuclear industry are accomplished by rigidly controlling the plant emissions.

Control of radioactive pollution is accomplished by a variety of methods. Radioactive particulates are removed by filtration, electrostatic precipitation cyclones, or scrubbers. Gases and vapors are often removed by absorption or chemisorption. Storage is effective in eliminating those radionuclides which have a comparitively short half-life. Most reactors are required to have containment buildings to preclude the possibility of atmospheric contamination from an accident.

Estimates place the costs of controlling radioactive emissions from nuclear power plants at 10 percent of the total plant cost, or approximately $18,000,000 for a typical 800 Mw(e) reactor plant. No information has been found on the costs of damage resulting from radioactive air pollution.

Techniques are available for measuring atmospheric concentrations of radioactive substances with a high degree of accuracy and sensitivity.

Based on the material presented in this report, further studies are suggested in the following areas:

(1) Investigation of increase of emissions caused by the increased growth rate of commercial nuclear reactors to determine the future cumulative effects on ambient air concentrations of radioactive substances.

(2) Investigation of the effects on humans, animals, and plants of low-level, long-duration exposures to environmental concentrations of radioactive substances.

(3) Expansion of the investigation of the emission of radioactive materials from combustion of fossil fuels.

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APPENDIX A

APPENDIX A

A.1 Radiation[73,130,162]

Each radionuclide has a characteristic decay constant that is expressed in terms of the half-life, i.e., the time required for half the atoms of a particular radionuclide to disintegrate into another form. This period may range from less than a millionth of a second to billions of years. In the case of air pollution by a radionuclide with a short half-life, the atmospheric radioactivity decreases rapidly by itself if no fresh pollution occurs. However, if the pollutant has a long half-life, radioactive pollution may remain practically at a relatively constant level. Radionuclides emit three types of radiation: alpha rays carrying a positive charge, beta rays carrying a negative charge, and electromagnetic gamma rays. The energy of this radiation may vary from a very low value to several million electron volts (Mev). The effect on living organisms depends largely on the type of radiation emitted and its penetrating power, which is weak for alpha rays, medium for beta rays, and strong for gamma rays.

A.1.1 Alpha Radiation

Alpha radiations, positively charged particles that are identical with the nucleus of a helium atom, are emitted by some radioactive atoms with a kinetic energy of 4 to 10 Mev. Alpha particles emitted from most radioactive materials will travel only 1 to 8 cm in air, depending upon their energies. Since particles of these energies will generally be stopped by the inert surface layer of skin, alpha emitters present no problem from external radiation but can produce serious damage if ingested.

A.1.2 Beta Radiation

Beta radiations are electrons emitted from the nucleus of a radioactive atom with an energy of 0.02 to 3.2 Mev. External beta radiation with kinetic energy above about 0.1 Mev will penetrate the protective layer of the skin and cause skin burns. It will not penetrate to the deep-seated organs and therefore, damage is largely confined to the surface layers of the body, including such exposed organs as the eyes.

A.1.3 Gamma Radiation

Gamma radiations are short wavelength electromagnetic rays emitted from the nucleus of radioactive atoms. They are indistinguishable from X-rays. Gamma rays are extremely penetrating, and dense materials such as lead or depleted uranium are used to stop them or provide a shield against them.

A.2 Radiation Units

Special radiation units have been defined to permit measurement of radiation relative to the effects it produces. Damage to tissue is related to the amount of energy deposited by radiation in the tissue. Some common radiation units are defined as follows:

(1) Rad

The rad is the basic unit of absorbed dose in ionizing radiation. A dose of 1 rad is defined as the deposition of 100 ergs of radiation per gram of absorbing material (International Commission on Radiological Units and Measurements, 1962).

(2) Roentgen (r)

The roentgen is the unit of measurement for radiation exposure. It is defined as the amount of gamma or X-radiation required to produce ions carrying 1 electrostatic unit (esu) of electricity, either positive or negative, in 1 cm of dry air at standard conditions.

Since the roentgen is a measure of the interaction of gamma radiation and air, the absorbed dose (in rads) will vary in different materials for the same exposure (in roentgens). With moderate-energy gamma rays (0.2 to 3 Mev), an exposure of 1 r will produce an absorbed dose in muscle of about 0.97 rads.

(3) Absorbed Dose (rems)

All radiations do not produce identical biological effects for a given amount of energy delivered to the tissues. The relative biological effectiveness factor (RBE) is used to compare the effectiveness of absorbed doses of radiation from different types of ionizing radiation. RBE is defined as the inverse rate of the amount of absorbed radiation required to produce a given effect to a standard (or reference) radiation required to produce the same effect. The absorbed dose in rems is the unit of dose of any ionizing radiation which produces the same biological effect as a unit of absorbed dose of ordinary X-rays. The relationship between the absorbed dose in rems and the absorbed dose in rads is

dose rems = RBE x absorbed dose, rads.

The RBE for different types of radiation are shown in Table 28, Appendix B.

(4) Curie (Ci*)

The curie is the basic unit used to describe the intensity of radioactivity in a sample of material. One curie is that quantity of a radioactive nuclide in which the number of disintegrations per second is exactly 3×10^{-10}. This is approximately the rate of decay of 1 gram of radium.

The relation between the rate of disintegration of radioactive material (curie) and the radiation dose rate (rad/sec) is dependent upon the energy of the radiation emitted, the type of radiation emitted, the geometrical pattern between the radioactive material and the receptor, and the amount of absorbing material between the radioactive material and the receptor.

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*1 micro curie (1 μCi) = 10^{-6} Ci = 3×10^{-4} disintegrations/sec.

1 pico curie (1 pCi) = 10^{-12} Ci = 10^{-6} μCi.

APPENDIX B

APPENDIX B

TABLE 1

REFERENCES TO STUDIES OF EFFECTS ON HUMANS[27]

Study Area	Number of References in Bibliography
Genetic and congenital effects	48
Effects on life span	41
Carcinogenesis	
Leukemia and prenatal exposure	42
Leukemia and exposure in children and adults	133
Neoplasms in children and adults treated for benign conditions in the neck and mediastinum	130
Neoplasms in patients with thyroid diseases treated with I-131 or X-ray	44
Bone neoplasms and radium	83
Neoplasms of the reticuloendothelial system and thorium	118
Pulmonary neoplasms and radon daughters	15
Other pathological effects	4

TABLE 2

AVERAGE IONIZING RADIATION DOSE RATE

Source	Dose Rate per Year	Reference
Natural radiation	75 to 175 mrad/yr	166
Medical exposure		140
Gonad dose from diagnosis (1964)	155 mrem/yr	
Gonad dose from therapeutic use (1964)	7 mrem/yr	140
Bone marrow dose from diagnosis (1964)	125 mrem/yr	140
Thyroid dose from diagnosis (mostly dental) (1964)	1,000 mrem/yr	140
Weapons fallout dose (1954-1965)	76 mrad Total	147
Weapons fallout dose (1966)	3 mrem/yr	140
Nuclear energy industry, gonad dose (1966)[a]	0.2 mrem/yr	
Nuclear industry, whole-body (2,060)	50 to 100 mrad/yr	43
All other occupational exposure, gonad dose (1966)[b]	0.4 mrem/yr	140
Other manmade sources (watches, televisions, shoe-fitting machines, radioisotope applications, etc.) gonad dose (1966)[c]	0.1 mrem/yr	140

[a] Nuclear industry genetically significant dose to the United States population.

[b] Based on estimates of dose received by medical personnel occupationally exposed in medical diagnoses and therapy.

[c] Federal Radiation Council[62,63] recommended nonmedical maximum dose to general public: whole body - 500 mrem/yr; gonad
- average dose for 30 yrs
5 rem is approximately
equal to 170 mrem/yr
for X-ray and beta particles, mrem is
the same as mrad.

APPENDIX B

TABLE 3

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES[74]

Range	0-100 Rems (Subclinical Range)	100 to 1,000 Rems (Therapeutic Range)			Over 1,000 Rems (Lethal Range)	
		100-200 Rems	200-600 Rems	600-1,000 Rems	1,000-5,000 Rems	Over 5,000 Rems
		Clinical Surveillance	Effective Therapy	Promising Therapy	Palliative Therapy	
Incidence of vomiting	None	100 rems: 5% 200 rems: 50%	300 rems: 100%	100%	100%	
Delay time		3 hr	2 hr	1 hr	30 min	
Leading organ	None	Hematopoietic tissue			Gastrointestinal tract	Central Nervous System
Characteristic signs	None	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rems		Diarrhea; fever; disturbance of electrolyte balance	Convulsions; tremor; ataxia; lethargy
Critical period, post-exposure			4 to 6 wk		5 to 14 days	1 to 48 hr
Therapy	Reassurance	Reassurance; hematologic surveillance	Blood transfusion; antibiotics	Consider bone-marrow transplantation	Maintenance of electrolyte balance	Sedatives

(continued)

TABLE 3 (Continued)

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

Range	0-100 Rems (Subclinical Range)	100 to 1,000 Rems (Therapeutic Range)			Over 1,000 Rems (Lethal Range)	
		100-200 Rems	200-600 Rems	600-1,000 Rems	1,000-5,000 Rems	Over 5,000 Rems
		Clinical Surveillance	Effective Therapy	Promising Therapy	Palliative Therapy	
Prognosis	Excellent	Excellent	Good	Guarded	Hopeless	
Convalescent period	None	Several wk	1 to 12 mo	Long		
Incidence of death	None	None	0-80% (variable)	80-100% (variable)	90 to 100%	
Period within which death occurs			2 mo		2 wk	2 days
Cause of death			Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema

APPENDIX B

TABLE 4

LETHAL RESPONSE OF MAMMALS AND FOWL TO BRIEF EXPOSURES OF NUCLEAR RADIATIONS[47]

Species	Source	Mean Energies (Mev)	LD50/30[a]	(95% C.I.)[b]	Rate (r/hr)
Burro	Co^{60}	1.25	784	753-847	50
Burro	Ta^{182}	1.20-0.18	651	621-683	18-23
Burro	Zr^{95}-Nb^{95}	0.74	585	530-627	19-20
Swine	Co^{60}	1.25	618	525-682	50
Sheep	Zr^{95}-Nb^{95}	0.74	524		20
Cattle	Co^{60}	1.25	540	520-570	25
Swine	X-ray	1.0	555	418-671	180
Swine	X-ray	2.0	388	323-441	90
Burro	neutron/gamma	various	402		
Poultry					
Males	Co^{60}	1.25	600	(estimated)	50
Females	Co^{60}	1.25	1,000	(estimated)	50
Chicks	X-ray	0.250 (peak)	900	(estimated)	very short

[a] $LD_{50/30}$ - 50 percent fatalities within 30 days.

[b] 95 percent Confidence Index.

TABLE 5

CENSUS OF LABORATORY ANIMALS USED IN PROGRAMS OF THE DIVISION OF BIOLOGY AND MEDICINE, U.S. ATOMIC ENERGY COMMISSION (AS OF SEPT. 1, 1966)[148]

Animal	Number Used
Alligator	1
Cats	239
Cattle	541
Chickens	5,809
Chicks	6,400
Chinchillas	38
Chipmunks	34
Cichlids	50
Deer	15
Dogs (beagles)	2,091
Dogs (miscellaneous breeds)	494
Drosophila	*
Ducks	78
Eels	312
Equines (burros, ponies, horses)	40
Ferrets	30
Fish (miscellaneous)	184
Fowl (miscellaneous	500
Frogs	2,638
Gerbils	8
Goats	106
Grasshoppers	2,800
Guinea pigs	4,130
Hamsters	5,607
Mastomys	8
Mice	783,615
Mice (wild)	140
Muskrat	1
Mussels	200
Oppossum	1
Pigeons	115
Primates	369
Quail	100
Rabbits	8,437
Raccoons	4
Rats	111,084
Salamanders	411
Salamanders (necturi)	58

(continued)

TABLE 5 (Continued)

CENSUS OF LABORATORY ANIMALS USED IN PROGRAMS OF THE DIVISION OF BIOLOGY AND MEDICINE, U.S. ATOMIC ENERGY COMMISSION (AS OF SEPT. 1, 1966)

Animal	Number Used
Salmon	4,264,000
Sea urchins	500
Sheep	391
Snails	50
Squirrels	298
Swine	7,047
Swine, miniature	1,053
Toads	579
Trout	1,201,550
Turtles	50

*Many millions, too numerous to count.

APPENDIX B

TABLE 6

MAXIMUM PERMISSIBLE DOSES FOR RADIATION WORKERS[133]

Organ	Annual MPD (rem)
Gonads, red bone marrow, and whole body	5*
Skin, thyroid, and bone	30
Hands and forearms, feet and ankles	75
All other organs	15

*The cumulative dose of D = 5(N-18) rem should not be exceeded. Here D (rem) is the cumulative dose and N (years) is the age of the individual.

APPENDIX B

TABLE 7

SELECTED PARAMETERS OF THE STANDARD MAN[162]

Parameters	Amounts
Total body weight	70,000 g
Skeleton	
Without bone marrow	7,000 g
Red marrow	1,500 g
Yellow marrow	1,500 g
Contents of GI tract	
Lower large intestine	150 g
Stomach	1,100 g
Small intestine	135 g
Upper large intestine	1,700 g
Liver	1,500 g
Lungs	700 g
Kidneys	300 g
Spleen	150 g
Testes	30 g
Thyroid	20 g
Water intake in food and fluids	2,200 g/day
Total air inhaled per day	2 X 10^7 cm^3

RENTENTION OF PARTICLES

Distribution	Readily soluble Compounds, (percent)	Other Compounds (percent)
Exhaled	25	25
Deposited in upper respiratory passages and later swallowed	50	50
Deposited in lungs	25[a]	25[b]

CONSTANTS FOR GI TRACT

Portion	Mass of Contents (grams)	Time of Food Arrival (hours)	Time of Food Leaving (hours)
Lower large intestine	150	13	31
Small intestine	1,100	1	5
Upper large intestine	135	5	13
Stomach	250	0	1

[a] Taken up into the body.

[b] One-half is eliminated from lungs and swallowed in first 24 hours. The remaining 12.5 percent is retained in lungs with a half-life of 120 days, except for plutonium and thorium, for which the biological half-life is assumed to be 1 year and 4 years, respectively.

APPENDIX B

TABLE 8

MPC FOR SOME SELECTED RADIONUCLIDES FOR GENERAL PUBLIC PROTECTION[34]

Isotope	MPC in Air (pCi/m^3)
Strontium-90	
Soluble	30
Insoluble	200
Ruthenium-103	
Soluble	3,000
Insoluble	200
Iodine-131	
Soluble	100
Insoluble	10,000
Cesium-137	
Soluble	2,000
Insoluble	5,000
Plutonium-239	
Soluble	0.06
Insoluble	1
Xenon-133	
Sub*	300,000
Krypton-85	
Sub*	300,000

*Sub: Submersion in a semispherical infinite cloud of air.

APPENDIX B

TABLE 9

RADIOACTIVE EMISSIONS FROM FOSSIL-FIRED POWER PLANTS[34,176]

Type of Plant	Critical Pollutant	Exposure Vector	Concentration Standards (pCi/m^3)	Discharge Quantities per MW/yr
Coal	^{226}Ra	Air-lungs	0.1	17.2 μCi
	^{228}Ra	Air-lungs	0.3	10.8 μCi
Oil	^{226}Ra	Air-lungs	0.1	0.15 μCi
	^{228}Ra	Air-lungs	0.3	0.35 μCi
Gas	Particulates: Radon Daughters	Air-lungs	unknown	unknown

APPENDIX B

TABLE 10

SUMMARY OF MEASUREMENTS OF NATURAL RADIOACTIVITY IN GROUND-LEVEL AIR[103]

Site	Period of Observation	Radioactivity (pCi/m^3) ^{214}Pb	Radioactivity (pCi/m^3) ^{212}Pb
Wales, Alaska	1953-59	20	0.16
Kodiak, Alaska	1950-60	9.9	0.04
Washington, D.C.	1950-61	122	1.34
Yokosuka, Japan	1954-58	56	0.48
Lima, Peru	1959-62	42	1.33
Chacaltaya, Bolivia	1958-62	40	0.53
Rio de Janeiro, Brazil	1958-62	51	2.54
Little America, Antarctica	1956-58	2.5	<0.01
South Pole	1959-62	0.47	<0.01

APPENDIX B

TABLE 11

ENVIRONMENTAL RADIATION LEVELS MEASURED IN PRINCIPAL UNITED STATES CITIES[166]

City	Range of Radiation Levels (μr/hr)	Mean Annual Dose (mrad)	Cosmic Radiation (μr/hr)
Little Rock, Ark.	15.5-16.1	129	3.9
Colorado Springs, Colo.	22.5-26.4	197	8.7
Denver, Colo.	18.2-22.9	172	7.9
Grand Junction, Colo.	19.2-20.8	159	7.2
Bridgeport, Conn.	10.8-13.8	100	3.8
Hartford, Conn.	11.9	97	3.8
New Haven, Conn.	8.7- 9.1	73	3.8
Washington, D.C.	11.1-13.3	99	3.9
Chicago, Ill.	12.2-13.9	105	4.1
Portland, Maine	12.5-13.5	106	3.8
Baltimore, Md.	9.0-12.1	86	3.9
Boston, Mass.	11.0-14.3	103	3.8
Springfield, Mass.	12.9-13.9	109	3.8
Worcester, Mass.	14.0-16.4	124	4.0
Minneapolis-St. Paul, Minn.	10.6-15.0	109	4.2
Albuquerque, N.Mex.	15.7-16.5	132	7.5
New York, N.Y.	8.2-15.6	91	3.8
Charlotte, N.C.	10.6	86	4.1
Raleigh, N.C.	12.1-13.5	108	4.0
Winston-Salem, N.C.	12.9-14.7	112	4.3
Cleveland, Ohio	12.4-14.1	108	4.2
Toledo, Ohio	10.1-11.8	89	4.1
Oklahoma City, Okla.	11.5-12.3	99	4.6
Tulsa, Okla.	12.8-13.9	109	4.2
Harrisburg, Pa.	11.3-14.3	104	4.0
Philadephia, Pa.	11.7-12.5	99	3.8
Pittsburgh, Pa.	11.5-16.8	114	4.3
Providence, R.I.	11.1-13.8	101	3.8
Charleston, S.C.	13.5-14.5	114	3.7
Columbia, S.C.	15.0-15.2	123	3.9
Sioux Falls, S.Dak.	13.6-14.0	112	4.5
Chattanooga, Tenn.	13.2-14.8	114	4.0
Memphis, Tenn.	11.0-13.2	99	3.9
Amarillo, Tex.	14.9-15.8	126	6.4
Lynchburg, Va.	12.4-15.4	113	4.2
Richmond, Va.	9.8-11.1	85	3.9
Madison, Wis.	11.8-12.2	98	4.3
Cheyenne, Wyo.	19.8-20.4	164	8.5

TABLE 12

PROPERTIES OF COMMON RADIOACTIVE GASES[168]

Gas	Half-Life	Principal Sources
$^{131}I_2$	8.0 days	Reactors, bombs, chemical fuel processing
T_2*HTO	12.5 years	Reactors, accelerators
^{41}Ar	1.8 hours	Reactors
^{133}Xe	5.2 days	Reactors, fuel processing
^{135}Xe	9.2 hours	Reactors, fuel processing
^{85}Kr	10.0 years	Reactors, fuel processing
$^{14}CO_2$	5,700.0 years	Laboratories, bombs
$^{35}SO_2$	87.0 days	Laboratories
$^{13}N_2$	10.0 minutes	Accelerators
$^{15}O_2$	2.0 minutes	Accelerators
$^{106}RuO_4$	1.0 years	Fuel processing
^{222}Rn	3.8 days	Mines, mills, refineries

*Tritium.

APPENDIX B

TABLE 13

URANIUM ORE MILLING PLANTS[129]

Plant	Location
Anaconda Co.	Bluewater, N.Mex.
Atlas Corp.	Moab, Utah
Climax Uranium	Grand Junction, Colo.
Cotter Corp.	Canon City, Colo.
Federal-American Partners	Fremont County, Wyom.
Kerr-McGee Corp.	Grants, N. Mex.
Mines Development, Inc.	Edgemont, S. Dak.
Petrotomics Co.	Shirly Basin, Wyom.
Susquehanna-Western, Inc.	Falls City, Tex.
Union Carbide Corp.	Uravan and Rifle, Colo., and Globe, Wyom.
United Nuclear Corporation-Homestake Partners	Grants, N. Mex.
Utah Mining and Construction	Fremont County, Wyom.
Western Nuclear	Jeffrey City, Wyom.

TABLE 14

URANIUM CONVERSION AND ENRICHING PLANTS[129]

Plant	Location
Allied Chemical Corp.	Metropolis, Ill.
Kerr-McGee Ltd.	Sequoyah, Oklahoma (to be completed mid-1970)
Atomic Energy Commission	Oak Ridge, Tenn.
Atomic Energy Commission	Paducah, Ky.
Atomic Energy Commission	Portsmouth, Ohio

APPENDIX B

TABLE 15

PRODUCERS OF URANIUM FUELS[129]

Plant	Location
General Electric Co.	San Jose, Calif.
Gulf General Atomic, Inc.	San Diego, Calif.
Kerr-McGee Corp.	Oklahoma City, Okla.
National Lead Co.	Albany, N.Y.
Nuclear Fuel Services, Inc.	Erwin, Tenn.
Nuclear Materials and Equipment Corp.	Apollo, Pa.
United Nuclear Corp.	Hematite, Mo.

TABLE 16

FABRICATORS OF URANIUM FUELS[129]

Plant	Location
Aerojet-General Corp.	San Ramon, Calif.
Atomics International, Inc.	Canoga Park, Calif.
Babcock & Wilcox Co.	Lynchburg, Va.
Combustion Engineering, Inc.	Windsor, Conn.
General Electric Co.	San Jose, Calif.
Gulf General Atomic, Inc.	San Diego, Calif.
M & C Nuclear, Inc.	Attleboro, Mass.
National Lead Co.	Albany, N.Y.
Nuclear Fuel Services, Inc.	Erwin, Tenn.
Nuclear Materials and Equipment Corp.	Apollo, Pa.
Nuclear Metals Div., Whittaker Corp.	West Concord, Mass.
United Nuclear Corp.	New Haven, Conn.
Westinghouse Electric Corp.	Cheswick, Pa.

TABLE 17

POWER REACTORS[a][129]

Location		Startup	Location		Startup
Ala.	Browns Ferry	1970	Minn.	Elk River	1962
	Browns Ferry	1971		Monticello	1970
	Browns Ferry	1972		Red Wing No. 1	1972
Ark.	Dardanelle Lake	1972		Red Wing No. 2	1974
Calif.	Humboldt Bay	1963	Neb.	Fort Calhoun	1971
	San Clemente	1967		Brownville	1972
	Corral Canyon	1974	N.H.	Seabrook	1974
	Diablo Canyon No. 1	1972	N.J.	Toms River	1968
	Diablo Canyon No. 2	1974		Toms River	1972
	Sacramento County	1972		Artificial Island	1971
Colo.	Platteville	1971		Artificial Island	1973
Conn.	Haddam Neck	1967	N.Y.	Indian Point No. 1	1962
	Waterford No. 1	1969		Indian Point No. 2	1970
	Waterford No. 2	1973		Indian Point No. 3	1971
Fla.	Turkey Point No. 3	1970		Scriba	1968
	Turkey Point No. 4	1971		Rochester	1969
	Red Level	1972		Shoreham	1975
	Hutchinson Island	1973		Lansing	1973
Ga.	Baxley	1973		[b]	1973
Ill.	Morris No. 1	1959		Nine Mile Point	1973
	Morris No. 2	1968	N.C.	Southport	1973
	Morris No. 3	1969		Southport	1974
	Zion No. 1	1972		[b]	1976
	Zion No. 2	1973	Ohio	Oak Harbor	1974
	Quad Cities No. 1	1970	Oreg.	Rainier	1974
	Quad Cities No. 2	1971	Pa.	Peach Bottom No. 1	1966
Ind.	Burns Harbor	1970's		Peach Bottom No. 2	1971
Iowa	Cedar Rapids	1973		Peach Bottom No. 3	1973
Maine	Wiscasset	1972		[b]	1975
Md.	Lusby	1973		[b]	1977
	Lusby	1974		Shippingport	1957
Mass.	Rowe	1960		Shippingport	1973
	Plymouth	1971		Three Mile Island	1971
Mich.	Big Rock Point	1962		[b]	1975
	South Haven	1969		[b]	1977
	Lagoona Beach	1963	S.C.	Hartsville	1970
	Lagoona Beach	1974		Lake Keowee No. 1	1971
	Bridgman	1972		Lake Keowee No. 2	1972
	Bridgman	1973		Lake Keowee No. 3	1973
	Midland	1974	Tenn.	Daisy	1973
	Midland	1975		Daisy	1973

(continued)

TABLE 17 (Continued)

POWER REACTORS[a]

Location		Startup	Location		Startup
Vt.	Vernon	1970	Wash.	Richland	1966
Va.	Hog Island	1971	Wis.	Genoa	1967
	Hog Island	1972		Two Creeks No. 1	1970
	Louisa County	1974		Two Creeks No. 2	1971
				Carlton	1972

[a] Operable: 13; being built: 44; planned: 34.

[b] Site not selected.

TABLE 18

POWER-REACTOR WASTE-MANAGEMENT EXPERIENCE[18]

Reactor Parameters	Boiling-Water Reactors				Pressurized-Water Reactors	
	Dresden 1	Big Rock Pt.	Humboldt Bay	Elk River	Indian Pt. 1	Yankee
Power rating, MW						
Thermal	700	157	165	58	585	600
Electrical	200	50	52	24	163	185
Operational period reported	Oct. 1959- Dec. 1966	Sept. 1962- Apr. 1967	Feb. 1963- Feb. 1967	Oct. 1961- Mar. 1967	Aug. 1962- Sept. 1966	Jan. 1961 Dec. 1966
Gross electricity generated, MW-hr	6,600,000	1,053,000	1,055,000	393,000	3,489,000	6,362,000
Approximate capacity factor, %	65	45	80	70	50	70
Fuel cladding material	Stainless steel Zircaloy	Stainless steel	Stainless steel Zircaloy	Stainless steel	Stainless steel	Stainless steel
Maximum assemblies with defective cladding, %	5	15	25	15	0 (approx)	0 (approx.)
Gaseous wastes treatment	20-min delay, filtration	30-min delay, filtration	18-min delay, filtration	30-min delay, filtration	120-day delay, filtration	60-day dela filtration
Stack exhaust rate, cfm	44,000	30,000	12,000	3,000	280,000	15,000
Height of stack, ft	300	240	250	97	400	150
Permissible annual average release, ci/sec						
activation and noble gases	700,000	10^6	50,000	600	50,000	2,000
halogens and particulates		3.6	0.18	0.003	0.24	

(continued)

TABLE 18 (Continued)

POWER-REACTOR WASTE-MANAGEMENT EXPERIENCE

Reactor Parameter	Boiling-Water Reactors				Pressurized-Water Reactors	
	Dresden 1	Big Rock Pt.	Humboldt Bay	Elk River	Indian Pt. 1	Yankee
Range of annual average release activation and noble gases	<100-25,000 Ci/sec	<20-35,000 Ci/sec	40-14,100 Ci/sec	0-109 μCi/sec	0.07-1.6 μCi/sec	0.002-22 Ci/yr
Percent of limit	<0.02-3.6	<0.002-3.5	0.08-28	0-18	0.00013-0.0026	0.001-0.03
halogens and particulates	0.002-0.003	<1.2 μCi/sec	10^{-5}-0.07 Ci/sec	<3 X 10^{-5} Ci/sec	~2 X 10^{-8} Ci/sec	
Percent of limit		<30	1-38	<.1	<10^{-5}	

TABLE 19

FUEL REPROCESSING FACILITIES[129]

Plant	Location
Hanford (AEC)	Richland, Wash.
Savannah River (AEC)	Aiken, S.C.
NRTS (AEC)	Idaho Falls, Idaho
Nuclear Fuel Services	West Valley, N.Y.
General Electric	Morris, Ill. (Completion 1970)

TABLE 20

NUCLEAR FUEL CYCLE COST[129]
(Projected 1980 Costs in Millions of Dollars)

Cycle	Cost
Ore concentration	110
U_3O_8 conversion to UF_6	115
Enriching	1,030
Fabrication	630
Reprocessing	110
Total Fuel Cycle	2,500

APPENDIX B

TABLE 21

APPROXIMATE TOTAL YIELD OF ALL NUCLEAR WEAPONS TESTS THROUGH 1962[65]

Year	Megatons
1945-51	1
1952-54	60
1955-56	28
1957-58	85
1961	120
1962	217
Total	511

APPENDIX B

TABLE 22

COMMERCIAL USE OF NUCLEAR EXPLOSIONS (Plowshare Program)[71,135,152]

Project	Commercial Company	Purpose	Proposed Location	Status (July 1969)
Ketch	Columbia Gas Corp.	Fuel gas storage	To be determined	Looking for a site
Gas Buggy	El Paso Natural Gas Co.	Gas stimulation	Northeast New Mexico	Accomplished Dec. 1967. Results being calculated
Rulison	Austral Oil Co. and CER Geonuclear	Gas stimulation	North of Grand Junction, Colo.	Scheduled for Sept. 1970
	El Paso Natural Gas	Gas stimulation	Pinedale area of Wyoming	Proposed
	Wyoming Atomic Stimulation Project (WASP)	Gas stimulation	Pinedale area of Colorado	Proposed
Sloop	Kennecott Copper Corp.	Copper mining	Northeast of Stafford, Ariz.	Proposed for 1970
Rronco	CER Geonuclear and 15 oil and related companies	Recovery of oil from oil shale	Wyoming, Utah, and Colorado	Negotiating contract with Gov't. agencies

TABLE 23

GROSS BETA RADIOACTIVITY[2-5]
(pCi/m^3)

Location	1953-1957*		1958		1959		1960		1961		1962		1963		1964		1965	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Alabama	23.4	5.6	20.3	5.6	24.5	4.4	0.4	0.2	58.3	5.2	16.6	7.3	16.6	7.4	3.8	1.5	1.1	0.3
Alaska	11.0	.7	4.8	2.5	17.8	2.8	0.2	0.1	27.7	2.6	17.6	4.1	17.6	4.2	3.8	0.7	-	-
Arizona	731.9	67.0	63.7	13.8	52.1	6.6	1.9	0.2	108.0	7.2	40.0	9.8	40.0	9.5	8.0	2.1	8.8	0.6
Arkansas	71.3	7.5	16.5	4.9	17.5	4.3	0.4	0.1	43.9	4.1	20.0	6.2	20.0	6.4	5.5	1.3	0.7	0.3
California	350.0	2.5	126.0	8.1	33.8	4.3	0.9	0.1	73.7	4.9	31.2	5.8	31.2	5.8	6.5	1.2	1.4	0.3
Colorado	159.2	7.0	49.0	7.7	39.4	4.9	0.8	0.2	33.6	5.0	17.8	7.0	17.3	7.0	9.5	1.8	1.6	0.5
Connecticut	49.0	4.6	22.0	4.2	15.2	3.4	0.4	0.1	44.1	3.3	13.3	5.6	13.3	5.6	4.9	1.3	1.3	0.4
Delaware	52.6	6.0	12.0	4.9	19.5	3.5	0.5	0.2	29.3	3.6	12.8	4.9	12.8	5.0	8.4	1.5	1.3	0.3
District of Columbia	16.3	1.6	17.6	5.4	15.5	4.2	0.3	0.2	38.2	3.7	14.0	6.3	14.0	6.9	7.2	1.8	1.3	0.3
Florida	65.8	2.8	39.0	5.7	22.2	4.2	1.2	0.2	62.6	4.3	33.0	7.0	33.0	7.2	12.4	1.5	-	-
Georgia	53.3	3.4	24.2	5.2	27.9	4.2	0.4	0.2	51.2	3.9	18.2	6.5	18.2	6.4	3.8	1.3	1.0	0.3
Hawaii	5.2	1.8	17.1	4.4	16.1	3.2	0.6	0.1	26.9	2.2	16.8	4.0	8.3	4.0	2.2	0.9	3.0	0.3
Idaho	142.3	15.2	59.8	8.0	27.9	4.6	0.3	0.2	35.2	4.2	19.0	7.6	11.9	7.5	5.5	1.6	1.4	0.5
Illinois	72.1	2.4	25.0	5.7	21.4	3.6	0.3	0.1	29.7	3.6	16.3	6.1	16.3	6.1	4.5	1.3	1.5	0.3
Indiana	48.6	4.5	15.7	4.9	13.5	3.4	0.8	0.1	42.2	3.2	15.8	5.8	15.8	5.8	4.1	1.3	1.8	0.3
Iowa	70.5	9.5	15.9	4.3	16.9	4.1	0.4	0.2	20.1	3.1	16.1	5.6	16.1	5.5	3.6	1.2	1.1	0.3

(continued)

TABLE 23 (Continued)

GROSS BETA RADIOACTIVITY
(pCi/m^3)

Location	1953-1957*		1958		1959		1960		1961		1962		1963		1964		1965	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Kansas	324.0	16.8	68.2	10.1	16.3	3.5	0.5	0.2	22.3	3.0	16.2	6.4	16.2	6.3	3.8	1.2	1.6	0.3
Kentucky	72.8	2.9	7.2	3.2	12.8	3.2	-	-	37.4	4.7	-	-	-	-	6.5	1.5	1.4	0.3
Louisiana	142.7	3.7	26.4	6.7	19.4	3.7	0.7	0.2	262.9	9.4	95.8	8.5	95.8	8.4	6.8	1.4	1.3	0.3
Maine	3.8	1.8	29.0	5.2	24.7	4.3	0.4	0.1	32.5	3.0	15.8	5.3	15.8	5.3	3.9	1.3	1.3	0.3
Maryland	14.8	3.1	15.0	3.6	15.2	3.5	0.3	0.1	33.7	3.5	16.7	5.9	16.7	5.8	5.7	1.7	2.4	0.3
Massachusetts	58.8	3.3	33.0	4.5	71.0	3.8	0.5	0.1	53.0	2.2	22.4	6.1	22.4	6.2	4.4	1.2	2.0	0.4
Michigan	70.6	2.7	16.4	4.0	18.4	3.7	0.4	0.1	36.1	4.4	17.2	5.3	17.2	5.3	4.3	1.5	1.5	0.3
Minnesota	46.8	1.9	20.3	4.1	11.5	3.1	0.3	0.2	31.7	3.1	13.8	5.6	13.8	5.7	3.2	1.1	0.8	0.3
Mississippi	56.2	11.6	20.9	5.1	-	-	0.3	0.1	247.9	12.6	15.4	6.0	15.4	5.9	-	-	1.6	0.3
Missouri	120.1	4.1	31.8	6.1	25.4	4.7	0.3	0.1	26.0	3.5	20.1	7.3	20.1	7.3	4.2	1.4	1.2	0.3
Montana	24.1	4.2	508.0	13.6	13.0	3.6	0.4	0.1	52.5	5.1	35.2	6.4	35.2	6.4	4.7	1.1	1.4	0.5
Nebraska	27.8	5.0	76.0	6.2	12.5	3.6	0.4	0.1	41.8	4.7	19.6	7.0	19.6	7.0	6.4	1.6	0.9	0.3
Nevada	380.0	43.6	66.0	12.0	20.3	5.7	0.8	0.2	53.7	6.9	26.0	10.9	26.0	9.9	4.9	1.8	1.9	0.5
New Hampshire	14.0	4.1	20.4	4.1	14.2	3.3	0.3	0.1	22.1	3.6	10.0	5.7	10.0	5.9	3.4	1.2	1.0	0.3
New Jersey	74.0	6.0	18.2	4.0	17.9	2.9	0.2	0.1	28.1	3.4	27.3	5.8	27.3	5.7	4.6	1.4	2.0	0.3
New Mexico	57.5	11.9	85.0	11.3	39.5	5.9	0.5	0.2	41.0	5.0	17.0	7.4	17.0	7.4	5.8	1.8	2.6	0.5

(continued)

TABLE 23 (Continued)

GROSS BETA RADIOACTIVITY
(pCi/m^3)

Location	1953-1957*		1958		1959		1960		1961		1962		1963		1964		1965	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
New York	26.8	2.0	20.6	4.3	29.0	4.3	0.4	0.1	81.0	3.8	25.2	6.0	25.2	6.0	5.7	1.3	1.2	0.4
North Carolina	23.4	3.5	34.5	5.9	14.6	3.9	0.4	0.2	39.0	4.2	29.0	7.6	29.0	7.7	10.4	1.5	1.4	0.4
North Dakota	33.1	6.4	22.0	3.8	11.0	2.5	0.4	0.1	29.4	3.2	29.8	6.4	29.8	7.1	6.1	1.3	-	-
Ohio	117.9	2.3	27.3	5.4	18.4	3.6	0.4	0.1	63.9	4.1	20.5	5.9	20.5	5.9	6.8	1.5	3.6	0.4
Oklahoma	53.5	8.1	17.0	4.9	15.3	3.9	0.4	0.2	243.7	7.5	24.5	6.7	24.5	6.8	5.0	1.3	1.3	0.3
Oregon	18.8	1.0	17.0	2.5	14.8	2.6	0.2	0.1	59.6	3.8	16.2	4.0	16.2	3.8	3.5	0.8	0.9	0.2
Pennsylvania	93.0	2.9	29.0	4.2	22.2	3.6	0.3	0.1	46.5	3.5	27.0	6.3	27.0	6.3	6.3	1.5	2.9	0.4
Puerto Rico	5.8	2.0	-	-	14.7	2.3	26.3	0.7	16.4	1.2	10.5	4.3	10.5	3.9	3.3	1.0	2.0	0.2
Rhode Island	6.4	1.5	17.2	5.6	11.0	3.0	0.3	0.1	29.7	3.4	10.7	4.2	10.7	4.2	5.1	1.4	2.0	0.4
South Carolina	68.5	7.8	21.0	6.6	22.0	4.2	0.5	0.2	32.0	4.9	20.0	7.2	20.0	7.2	5.1	1.4	1.3	0.4
South Dakota	54.9	7.6	26.5	6.1	26.5	5.7	0.5	0.1	28.0	5.2	64.8	7.5	64.8	8.9	4.9	1.5	0.9	0.3
Tennessee	271.7	7.2	30.8	5.9	18.2	3.8	0.5	0.2	75.6	4.4	20.6	6.4	20.6	6.5	5.7	1.5	1.2	0.3
Texas	193.1	4.8	33.5	5.5	19.3	4.3	0.8	0.1	227.7	4.8	398.0	8.5	398.0	8.5	8.3	1.5	1.8	0.4
Utah	5435.0	82.7	57.0	9.8	17.0	5.1	0.6	0.2	28.6	6.4	18.6	8.8	18.6	8.6	5.2	1.6	2.5	0.5
Vermont	18.8	2.8	14.0	3.1	21.0	3.1	0.3	0.1	19.6	2.1	11.3	5.5	11.3	5.5	4.2	1.2	1.4	0.4
Virginia	24.3	4.4	17.4	5.1	17.8	4.3	0.4	0.2	75.0	4.9	14.9	7.1	14.9	7.1	9.8	1.7	1.5	0.4

(continued)

TABLE 23 (Continued)

GROSS BETA RADIOACTIVITY
(pCi/m^3)

Location	1953-1957*		1958		1959		1960		1961		1962		1963		1964		1965	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Washington	7.9	1.3	18.0	5.3	-	-	0.3	0.1	23.2	2.5	14.3	4.2	14.3	4.2	1.9	0.6	0.8	0.2
West Virginia	82.6	2.9	16.3	4.7	20.3	3.6	0.5	0.2	16.3	2.9	11.2	5.6	11.2	5.5	6.8	1.6	1.3	0.4
Wisconsin	49.3	5.5	13.7	3.9	11.6	3.4	0.4	0.1	43.1	4.1	18.5	4.3	18.5	4.5	3.5	1.1	2.0	0.3
Wyoming	233.7	30.0	21.3	7.8	23.4	4.8	0.4	0.2	46.2	5.5	104.6	10.7	104.6	11.3	5.4	1.5	1.4	0.4

*Data in this column may include only one year or the average of all measurements made during these years.

APPENDIX B

TABLE 24

RADIOACTIVE SOLIDS REMOVAL IN THE NUCLEAR INDUSTRY[159]

Type of Equipment	Particle-size Range Mass Median (μ)	Efficiency(%)	Application
Simple settling chambers	>50	60-80	Rarely used except for chips and recovery operations
Cyclones, large diameter	>5	40-85	Precleaners in mining, ore-handling, and machining operations
Cyclones, small diameter	>5	40-95	Same as above
Mechanical centrifugal collectors	>5	20-85	Same as large-cyclone application
Baffle chambers	>5	10-40	Incorporated in chip traps for metal-turning
Spray washers	>5	20-40	Rarely used except occasionally for cooling hot gases
Wet filters	Gases and 0.1-25μ mists	90-99	Used in laboratory hoods and chemical-separation operations
Packed towers	Gases and soluble particles	90	Gas absorption and precleaning for acid mists
Cyclone scrubber	>5	40-85	Dealing with pyrophoric materials in machining and casting operations, mining, and ore handling; roughing for incinerators

(continued)

APPENDIX B

TABLE 24 (Continued)

RADIOACTIVE SOLIDS REMOVAL IN THE NUCLEAR INDUSTRY

Type of Equipment	Particle-Size Range Mass Median (μ)	Efficiency(%)	Application
Inertial scrubbers, power-driven	8-10	90-95	Dealing with pyrophoric materials in machining and casting operations, mining, and ore handling
Venturi scrubber	>1	99 for H_2SO_4 mist; for SiO_2, oil, smoke, etc. 60-70	Incorporated in air-cleaning train of incinerators
Viscous air conditioning filters	10-25	70-85	Filtering of general ventilation air
Dry spun-glass filters	5	85-90	Filtering of general ventilation air; precleaning from chemical and metallurgical hoods
Packed beds of graded glass fibers 1 to 20 μ, 40" deep	<1	99.90-99.99	Dissolver, off-gas cleaning
High-efficiency cellulose-asbestos filters	<1	99.95-99.98	Final cleaning for hoods, glove boxes, reactor air, and incinerators
All-glass web filters	<1	99.95-99.99	Same as above
Conventional fabric filters	>1	90-99.9	Dust and fumes in feed materials production
Reverse-jet fabric filters	>1	90-99.9	Same as above

(continued)

TABLE 24 (Continued)

RADIOACTIVE SOLIDS REMOVAL IN THE NUCLEAR INDUSTRY

Type of Equipment	Particle-Size Range Mass Median (μ)	Efficiency(%)	Application
Single-stage electrostatic precipitators	<1	90-99	Final cleanup for chemical and metallurgical hoods; uranium machining
Two-stage electrostatic precipitator	<1-5	85-99	Not widely used for decontamination

APPENDIX B

TABLE 25

RADIOACTIVE GAS REMOVAL METHODS IN NUCLEAR INDUSTRY[159]

Type of Equipment	Type of Gas	Removal Efficiency(%)	Application
Delay in storage	Noble gases	100	Depends on shielding and structural materials; used to hold up relatively small volumes for gaseous decontamination
Spray towers	Halogens, hydrogen fluoride	70-99	Precleaning or final cleaning on iodine removal
Packed towers	Radioiodine	95-99	Heated beryl saddles coated with $AgNO_3$
Adsorbent beds	Iodine and noble gases	99.95	Activated charcoal or molecular sieves; may be used to decay xenon; may be refrigerated
Limestone beds	Halogens, hydrogen fluoride	94-99.9	Experimental only; some hood applications
Liquefaction column	Noble gases	99.9	Used to recover small amounts
Stripping columns		90-95	Pilot studies only
Refrigerated carbon catalyst and carbon pellets	Xenon and krypton	99.9	Liquid nitrogen used for refrigerant; gases recovered by desorption

TABLE 26

COSTS FOR DRY MECHANICAL DUST COLLECTORS[68]

Type of Unit	Capacity (cfm)	Total Annual Cost ($/1,000 cfm/yr)	Cost Analysis (Percent of Total Cost) Purchase and Installation	Power	Maintenance and Repairs	Service Conditions
Settling chamber	4,000	103	3.7	17.5	78.8	Exhaust from graphite machining
Aerodyne	5,900	92	41.4	25.4	33.2	Incinerator flue gas
Rotoclone "D"	4,000	593	12.2	28.3	59.5	Exhaust from graphite machining
Cyclone	3,570	203	16.3	34.6	49.1	Exhaust from carpenter shop
(2) Cyclone (Ducon)	2,200	409	33.1	22.9	44.0	Incinerator flue gas
(2) Cyclone (A, B, C)	2,200	170	22.9	55.3	21.8	Exhaust from uranium machining
Cyclone (K & B)	8,090	135	17.8	69.6	12.6	Exhaust from uranium machining
Multicyclone (Dustex)	800	511	46.5	18.3	35.2	Exhaust from sintering furnace

TABLE 27

COST OF WET DUST COLLECTORS INSTALLED AT AEC SITES[68]
(Unit: Rotoclone N)

Capacity (cfm)	Total Annual Cost ($/1,000 cfm/yr)	Cost Analysis (Percent of Total Cost) Purchase and Installation	Power and Water	Maintenance and Repairs	Service Conditions
3,300	505	32.3	62.5	5.2	Exhaust from machine shop and foundry
5,500	422	20.5	74.8	4.7	Exhaust from machine shop and foundry
5,900	1,399	2.1	16.2	81.7	Exhuast from uranium refinery (U_3O_8)
13,000	547	4.9	41.5	53.6	Exhaust from uranium refinery (U_3O_8)

APPENDIX B

TABLE 28

RBE FOR TYPES OF RADIATION[73]

Type of Radiation .	RBE
X-rays or gamma rays	1
Beta particles	1
Fast neutrons	10
Thermal neutrons	4-5
Alpha particles	10-20